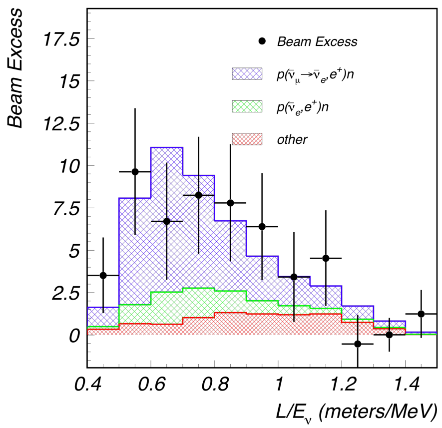
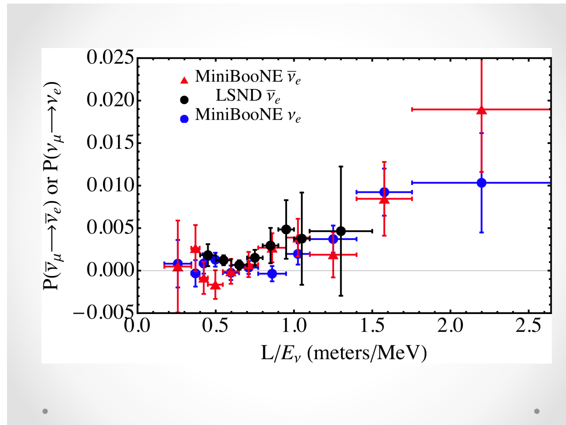
Overview of SBL Accelerator Neutrino Experiments

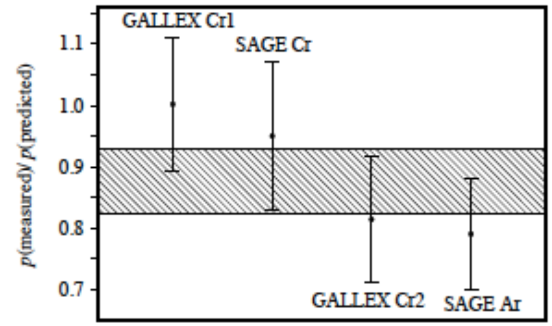
W.C. Louis, February 5, 2015

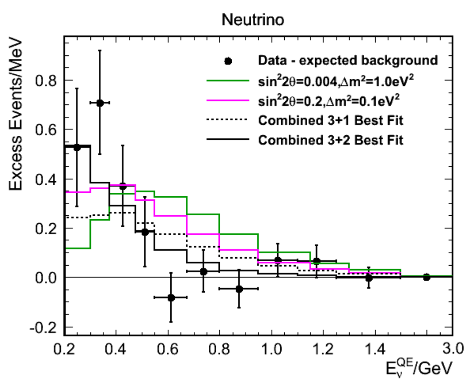
- Evidence for SBL Anomalies & 3+N Sterile Neutrino Models
- FNAL & J-PARC SBL Neutrino Programs
- Advantages of SBL Accelerator Neutrino Experiments
- Disadvantages (Caveats) of SBL Accelerator Neutrino Expts.
- More Exotic Possibilities
- Conclusions

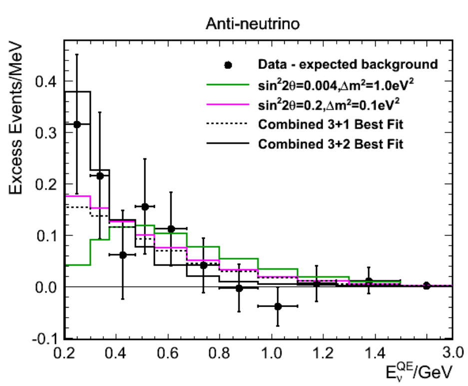
Short-Baseline Neutrino Anomalies

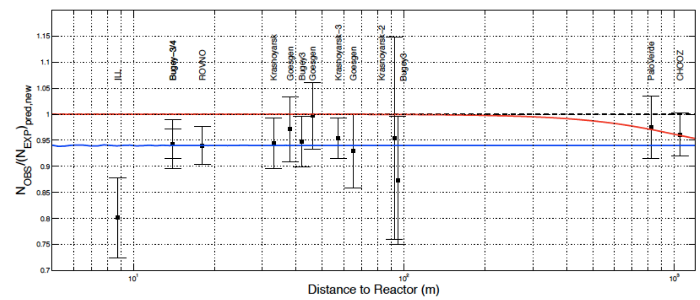


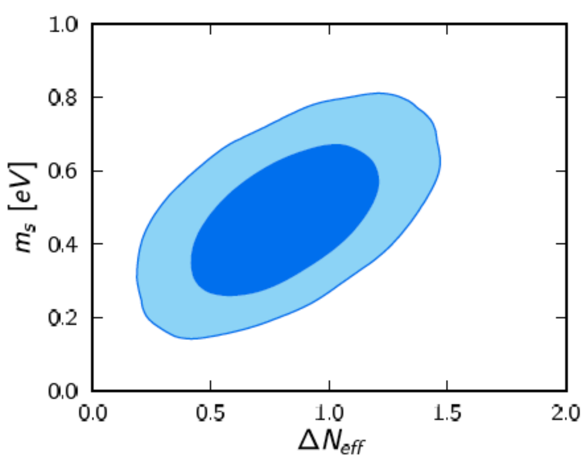




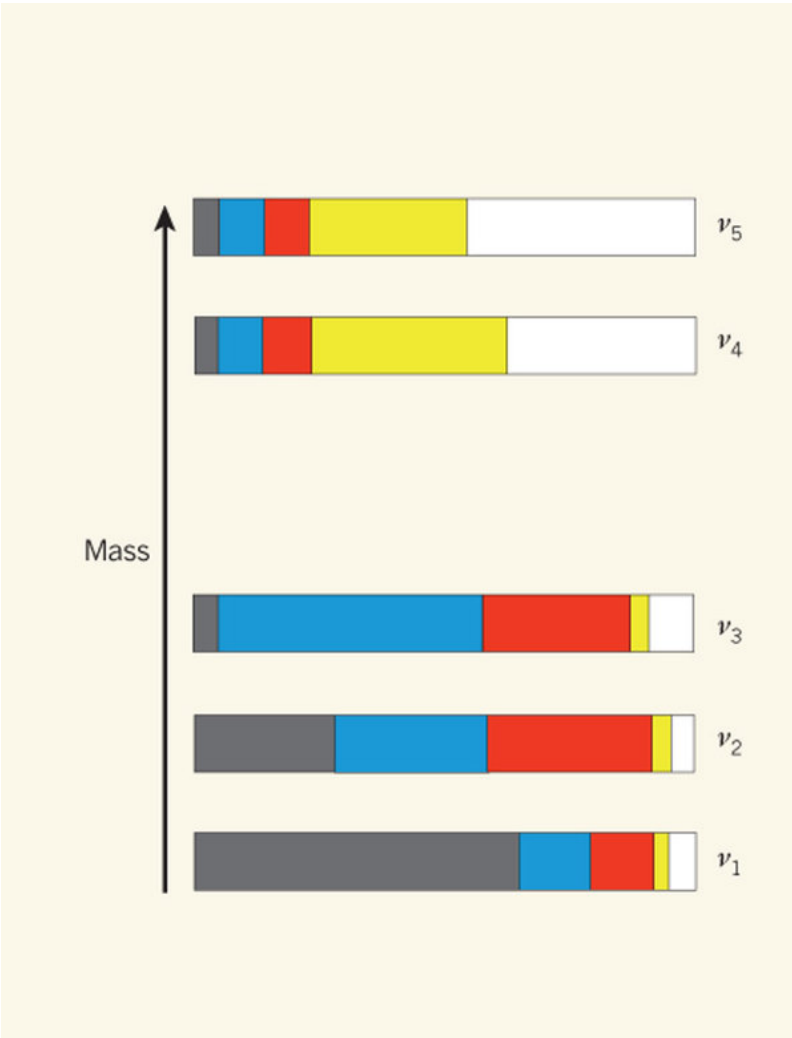








3+N Sterile Neutrino Models



- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \neq \nu_\mu \rightarrow \nu_e$

Note: There are also other, more exotic possibilities

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j \left|U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}\right| \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As #ν increases, the formalism gets rapidly more complicated!

#ν	#Δm_{ij}^2	#θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
4	3	6	3
5	4	10	6
6	5	15	10

Therefore, there needs to be ≥ 3 neutrino mixing for CP Violation!

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) \sim ¼\, P(\nu_\mu \rightarrow \nu_x)\, P(\nu_e \rightarrow \nu_x)$

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

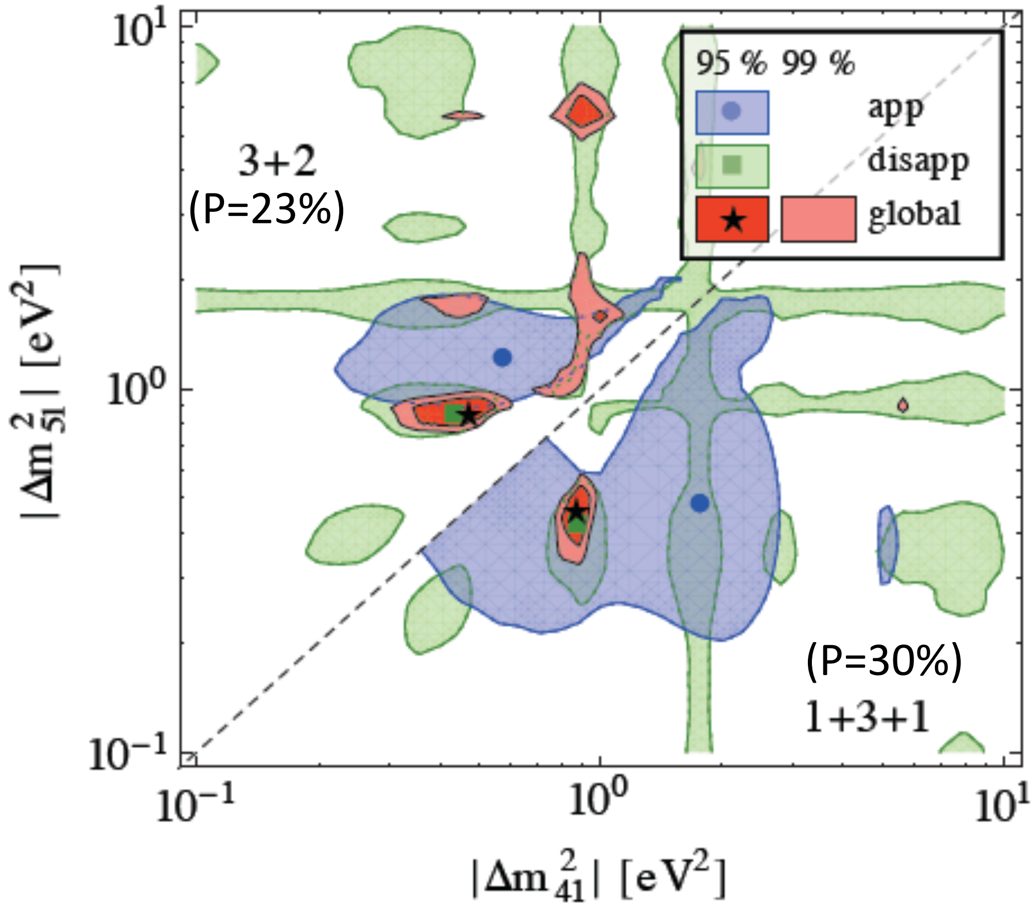
For 3+1 Models: $P(\nu_\mu \rightarrow \nu_e) = 4U^2_{e4}U^2_{\mu4} \sin^2(1.27\Delta m^2 L/E)$

$P(\nu_\mu \rightarrow \nu_x) = 4U^2_{\mu4}(1-U^2_{\mu4}) \sin^2(1.27\Delta m^2 L/E)$

$P(\nu_e \rightarrow \nu_x) = 4U^2_{e4}(1-U^2_{e4}) \sin^2(1.27\Delta m^2 L/E)$

Global 3+2 & 1+3+1 Fits

Kopp, Machado, Maltoni, & Schwetz, arXiv:1303.3011



Note that the Parameter Goodness of Fit probabilities are low due to tension between appearance and disappearance; however, no fake data studies have been performed.

Future Short-Baseline ν Experiments

• There is a diverse set of experiments, spanning vastly different energy Scales (from ~1 MeV to ~10 TeV), that have been proposed to test the 3+N models & resolve the present anomalies:

• Accelerator ν Experiments: MicroBooNE+LAr1+ICARUS, MINOS+, NuStorm , LBNE, OscSNS at ORNL, J-PARC E56, IsoDAR, nuPRISM

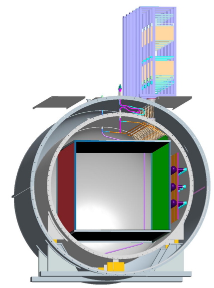
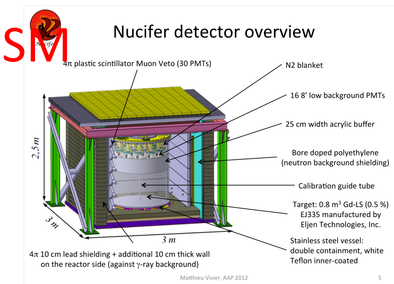
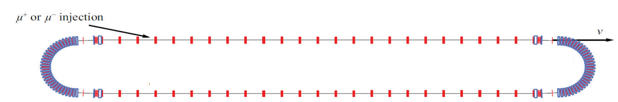


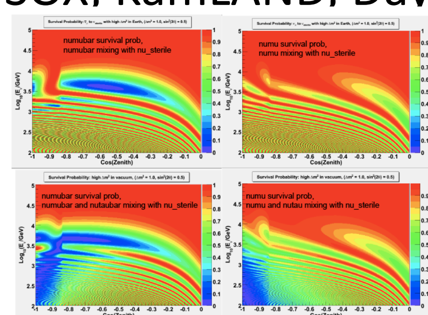
Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

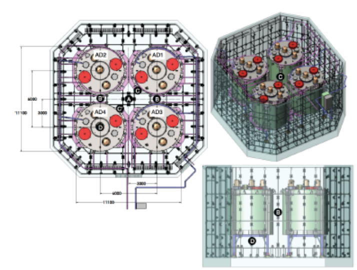




• Reactor ν Experiments: SCRAAM, NUCIFER, PROSPECT

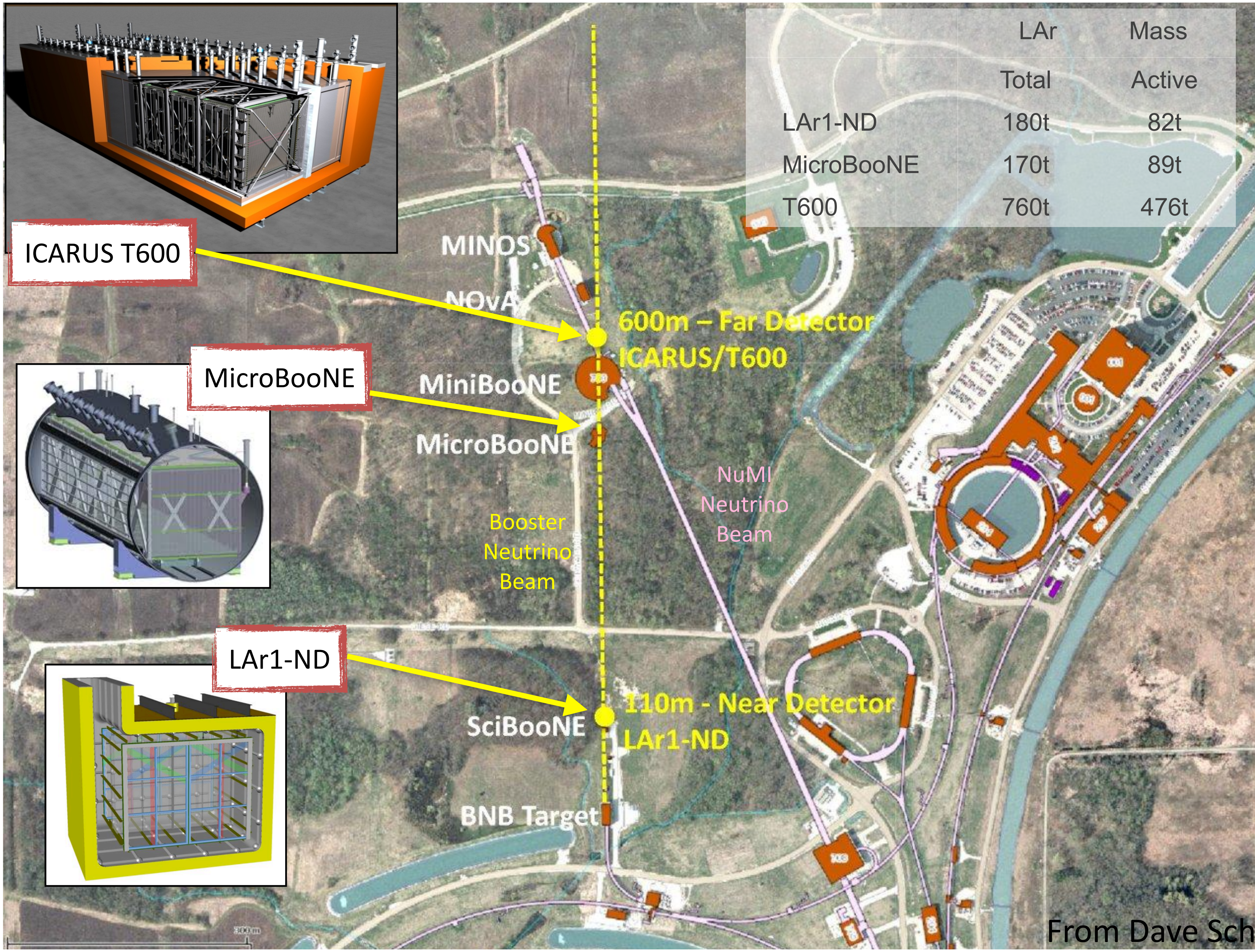
• Radioactive Source ν Experiments: BOREXINO-SOX, KamLAND, Daya Bay, Baksan, LENS





• Atmospheric ν Experiments: IceCube

SBN: A Multi-LAr TPC Short-Baseline Program at FNAL

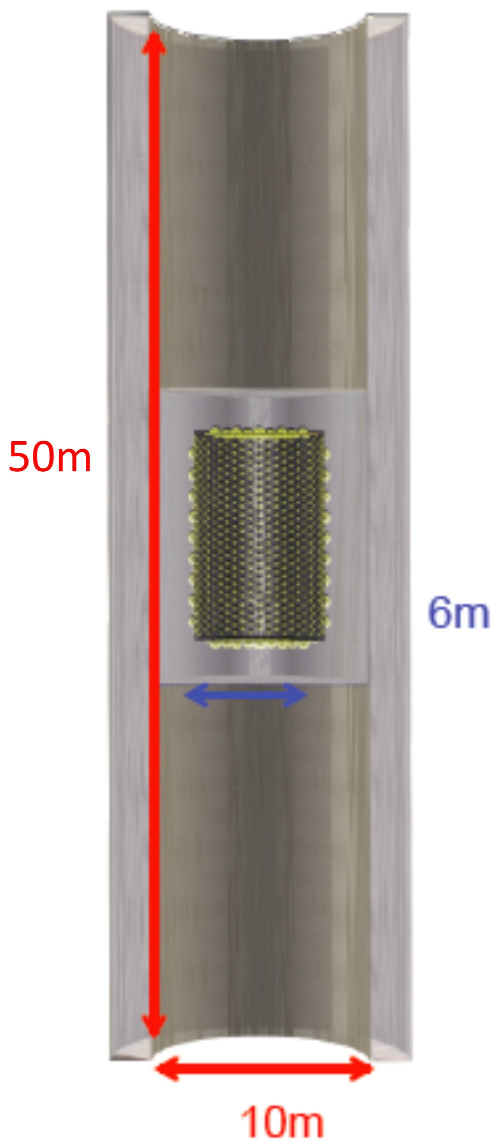


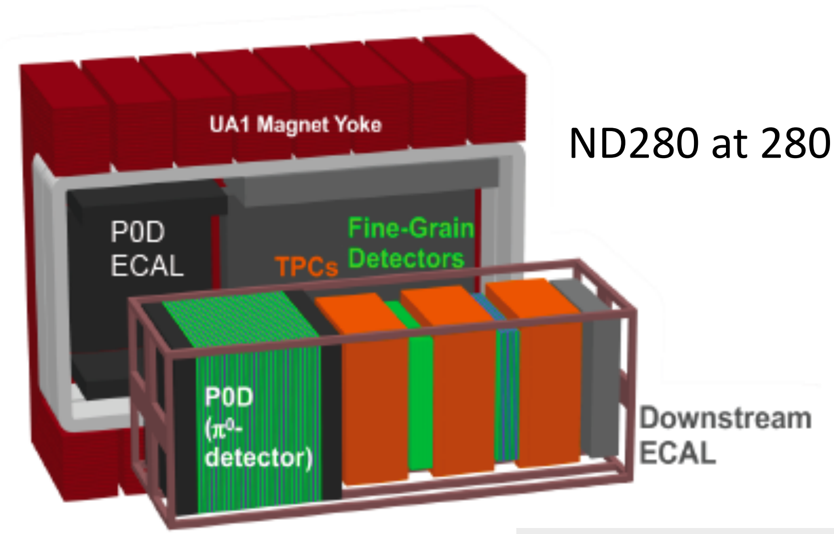
	LAr	Mass
	Total	Active
LAr1-ND	180t	82t
MicroBooNE	170t	89t
T600	760t	476t

From Dave Schmitz

T2K Beamline at J-PARC

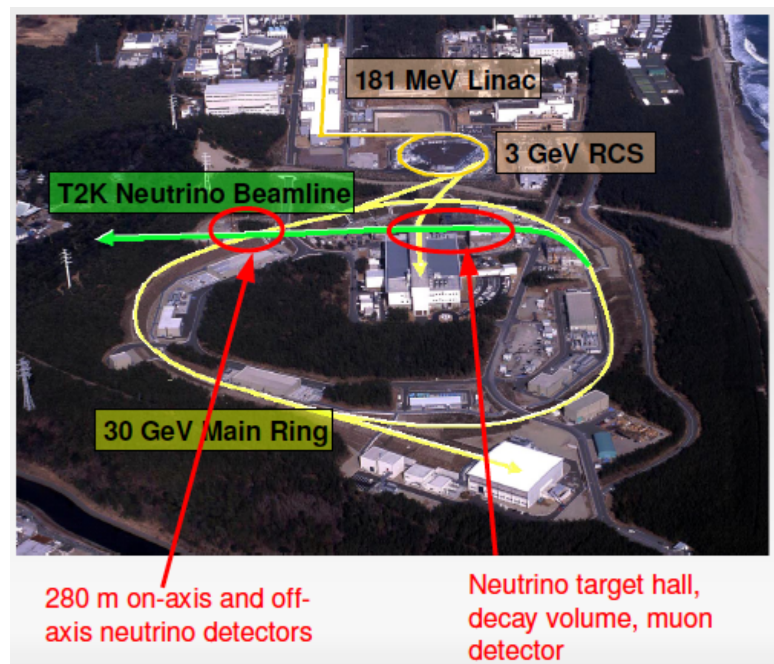
nuPRISM
at 1-2km





ND280 at 280m

By varying the angle, nuPRISM has better sensitivity for SBL oscillations and for measuring cross sections.



Advantages of SBL Accelerator Neutrino Experiments

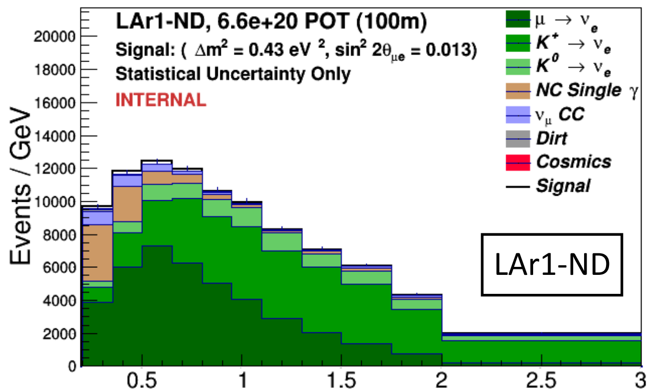
Can mount many detectors at different distances on the same beamline with approximately the same neutrino flux and with systematic uncertainties that mostly cancel. This is ideal for searching for ν_μ -> ν_e oscillations (& neutrino cross sections).

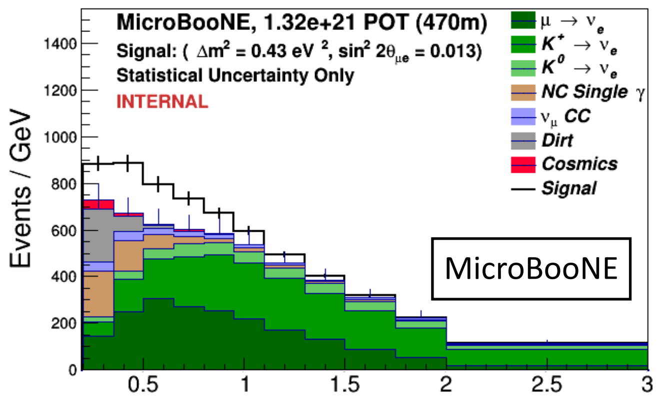
Also ideal for searching for ν_μ disappearance.

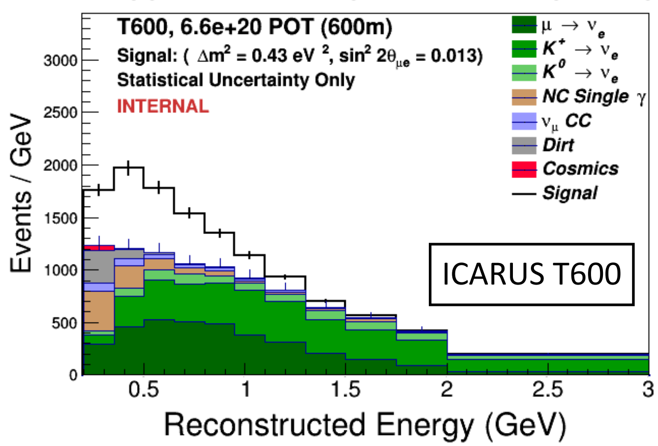
Can prove the existence of sterile neutrinos by searching for oscillations of a neutral-current reaction (e.g. NCπ^0 & NCEL).

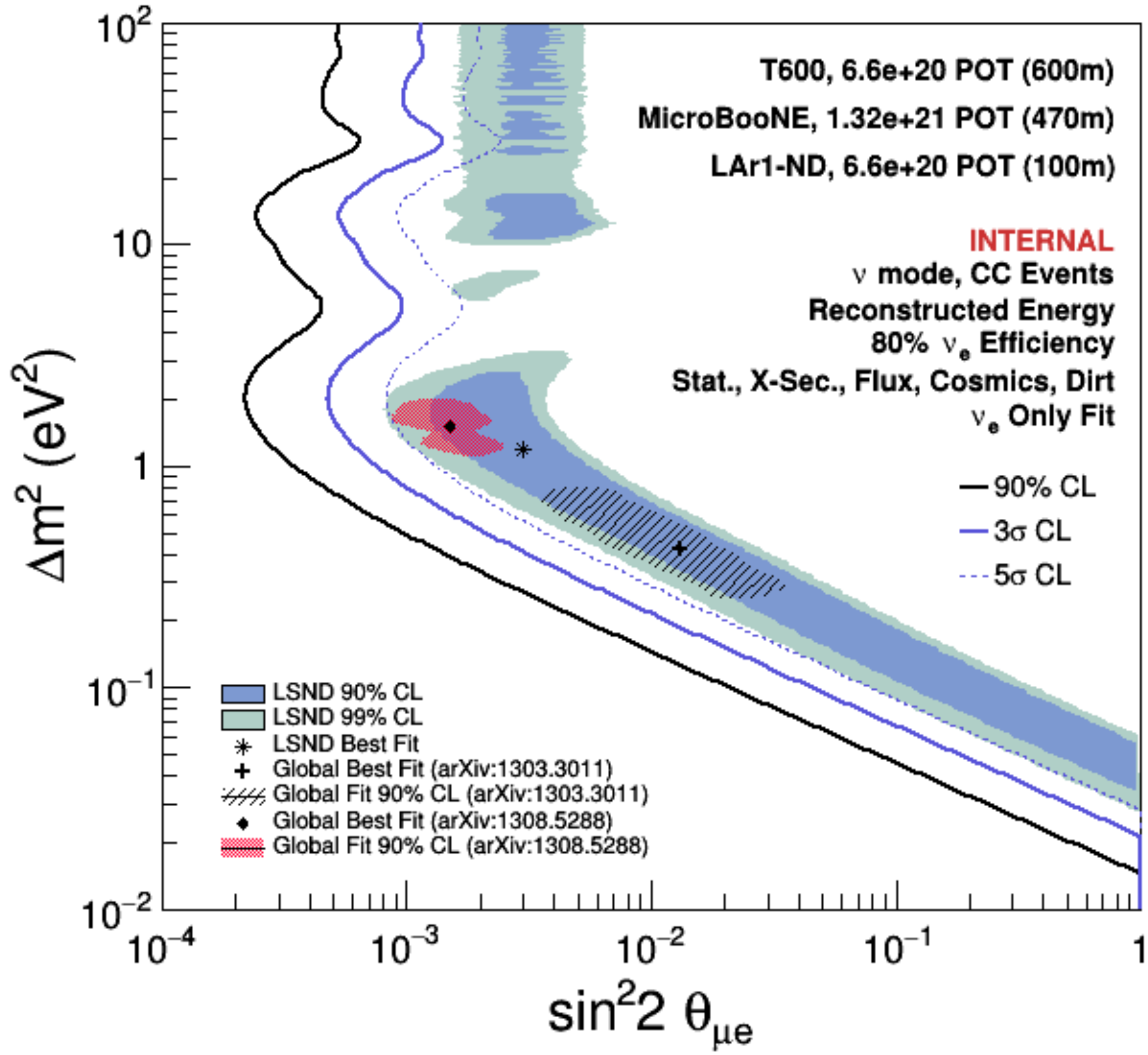
Can search for CP violation by searching for a difference between ν_e appearance and $\bar{\nu}_e$ appearance (although the antineutrino beam has a large neutrino contamination).

ν_e Appearance Sensitivity



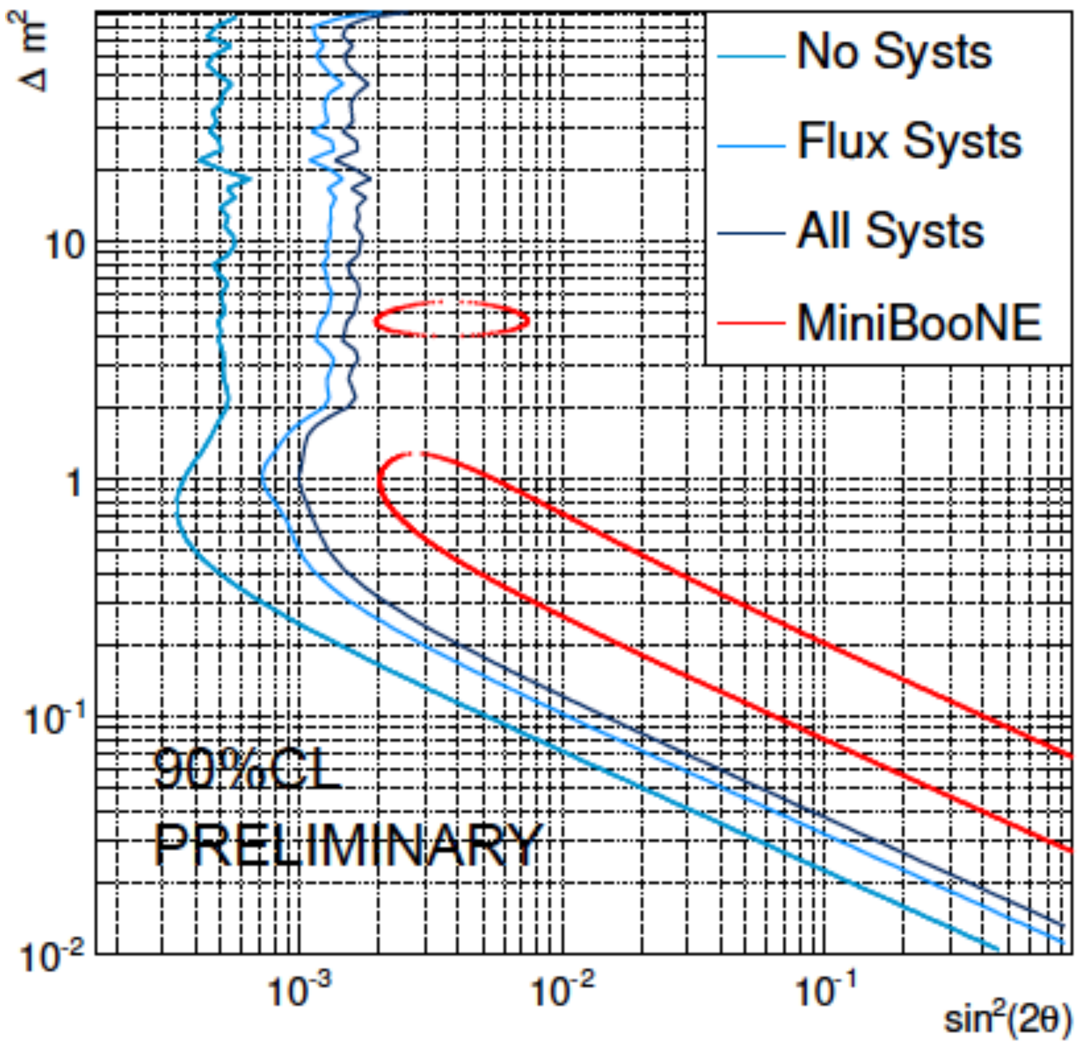






From Dave Schmitz

nuPRISM Sensitivity for ν_e Appearance



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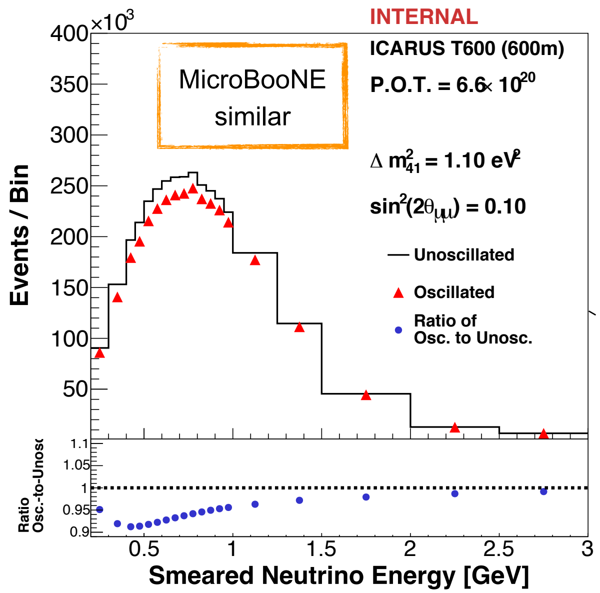
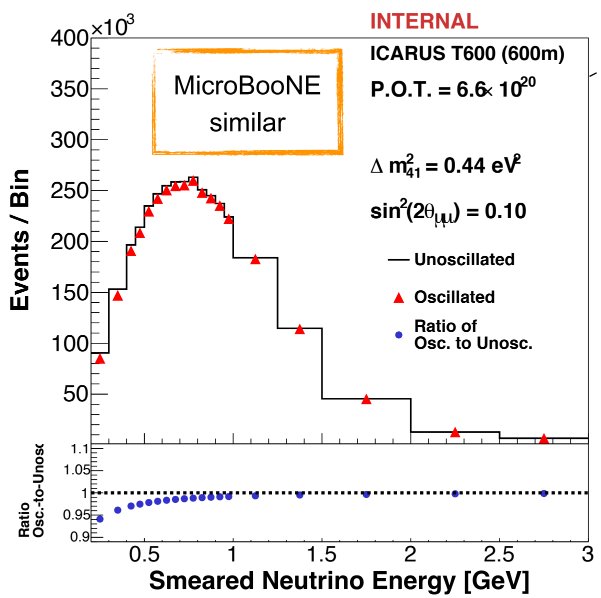
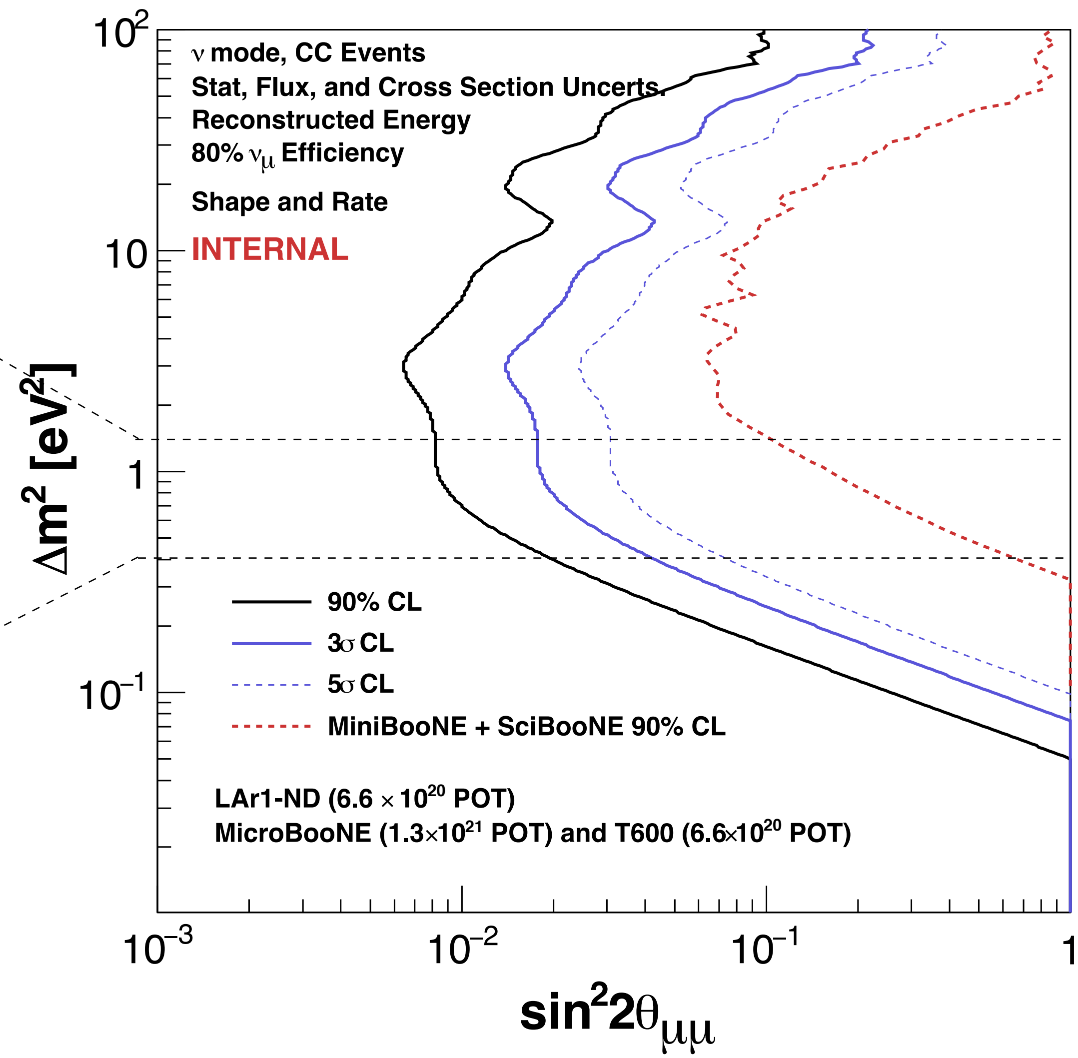
ν_μ Disappearance Sensitivity



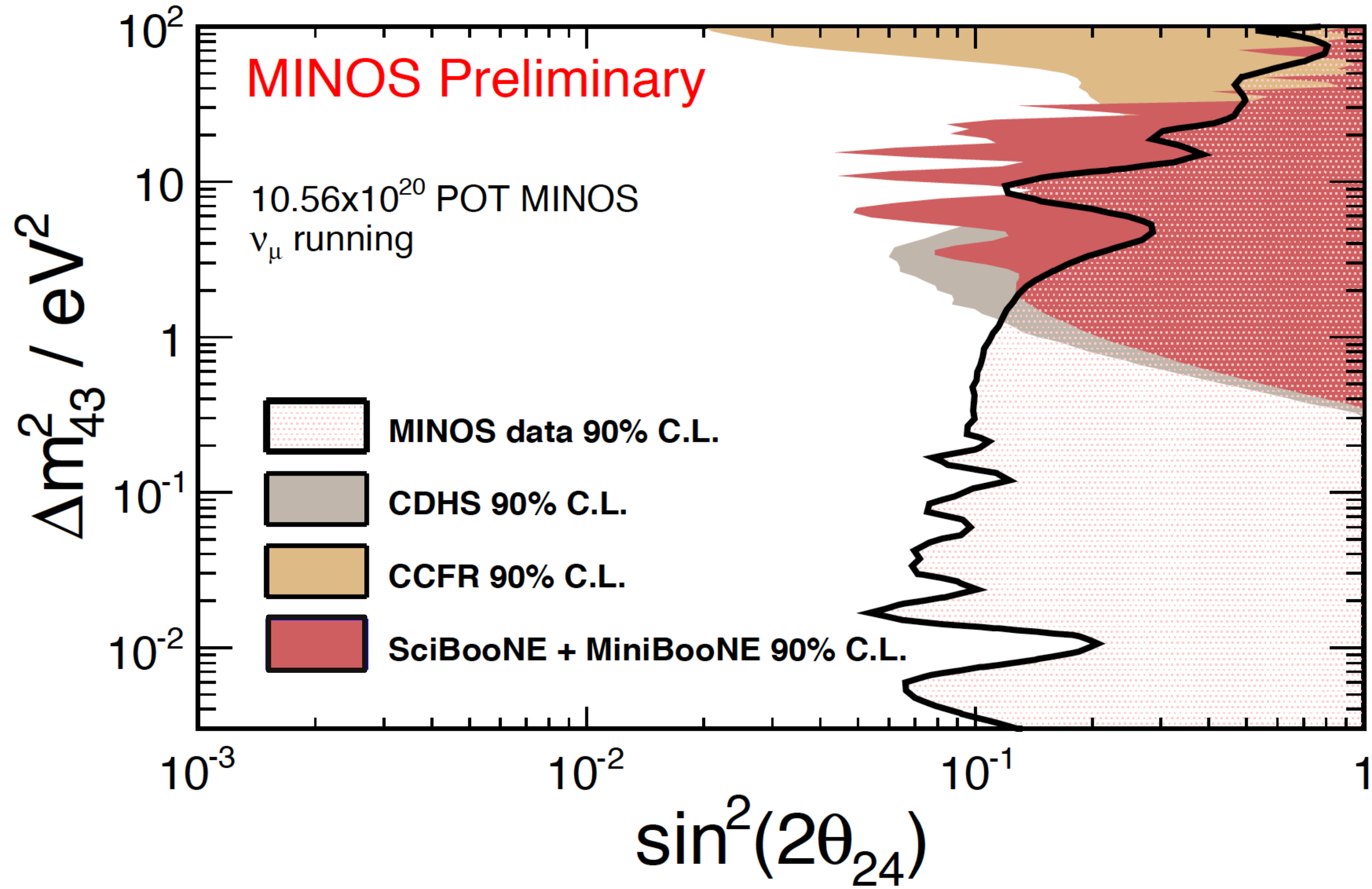




Sensitivity includes full flux and cross section systematics, but not detector systematics at this time.

From Dave Schmitz

MINOS Disappearance Limit



Future: MINOS+

- Limit is Feldman-Cousins corrected

MINOS 90% C.L. exclusion limit ranges over 4 orders of magnitude in Δm^2_{43}!
Strongest constraint on ν_μ disappearance into ν_s for $\Delta m^2_{43} < 1$ eV^2

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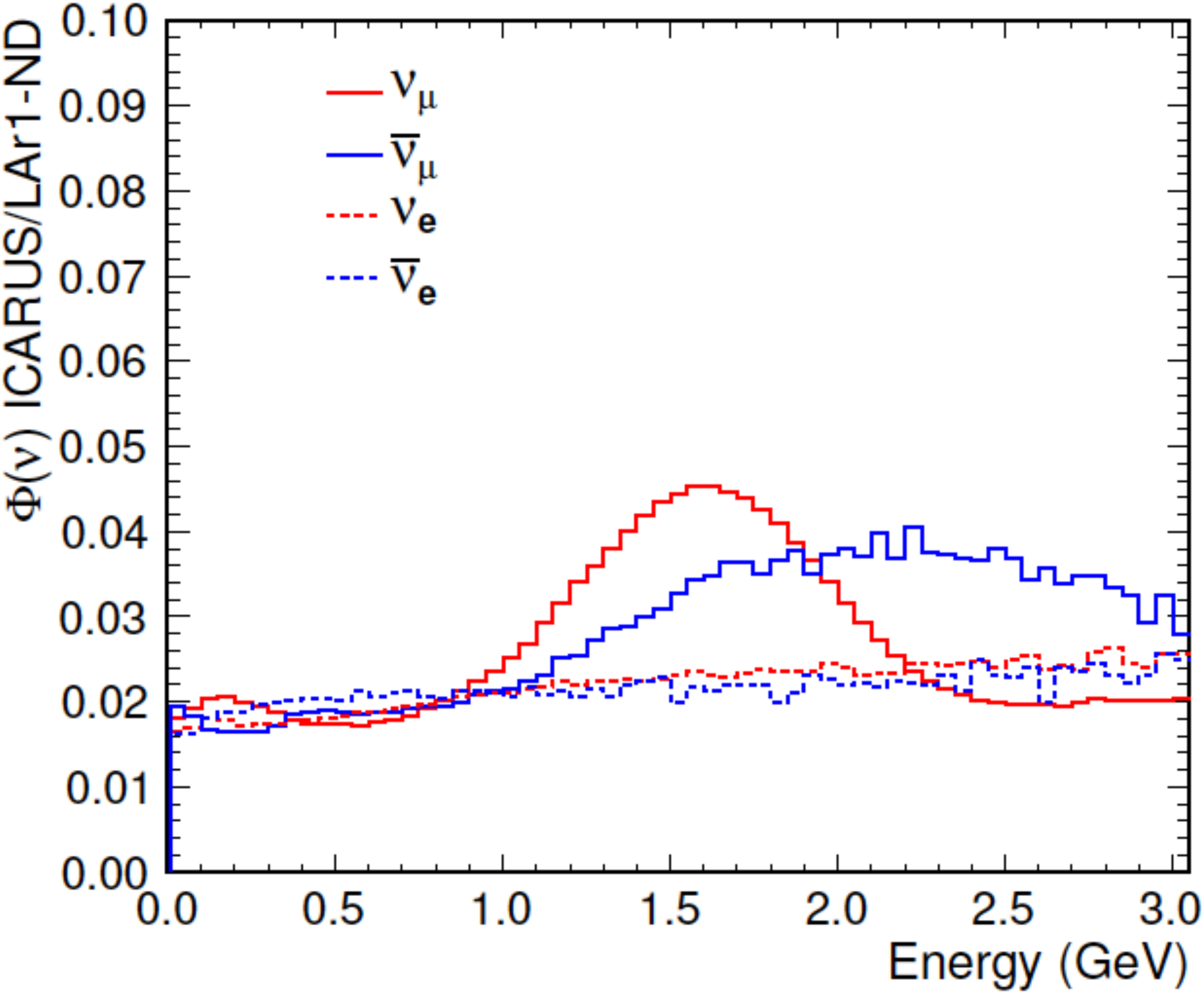
Disadvantages of SBL Accelerator Neutrino Expts.

Neutrino flux not identical at all locations (not a point neutrino source).

E_ν reconstruction is biased due to nuclear effects (e.g. 2-body currents) and this bias affects the determination of Δm^2 and $\sin^2 2\theta$. Even LAr TPCs will have some bias due to recoil neutrons and recoil protons below threshold.

ν_e appearance competes with ν_e disappearance, which is proportional to the intrinsic ν_e background. (There will be some cancellation.)

Note that $<\Delta m^2>$ and $<E_\nu>$ may be different for appearance and disappearance in 3+N models with N>1! For example, if $U_{e4}<U_{\mu 4}$ & $U_{e5}>U_{\mu 5}$, then $<E_\nu>$ for ν_e disappearance is greater than $<E_\nu>$ for ν_e appearance, which is greater than $<E_\nu>$ for ν_μ disappearance.



$\Phi(\nu)$ ICARUS/LAr1-ND
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

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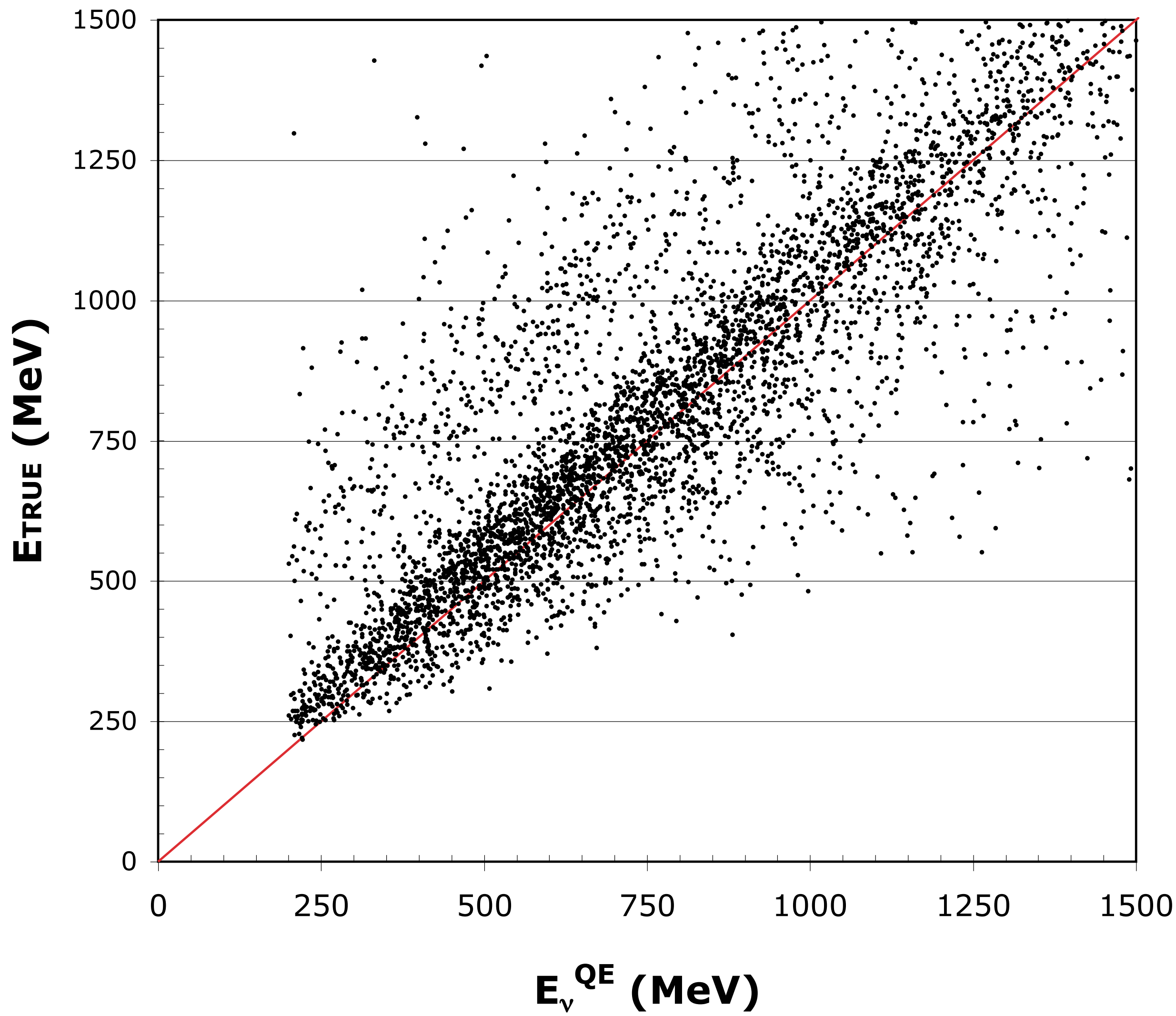
$\langle E_{true} \rangle > \langle E_{recon} \rangle$

(This Causes the Oscillation Probability to be Overestimated)

MiniBooNE MC Prediction w/o 2-body currents



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Binned log-likelihood fit

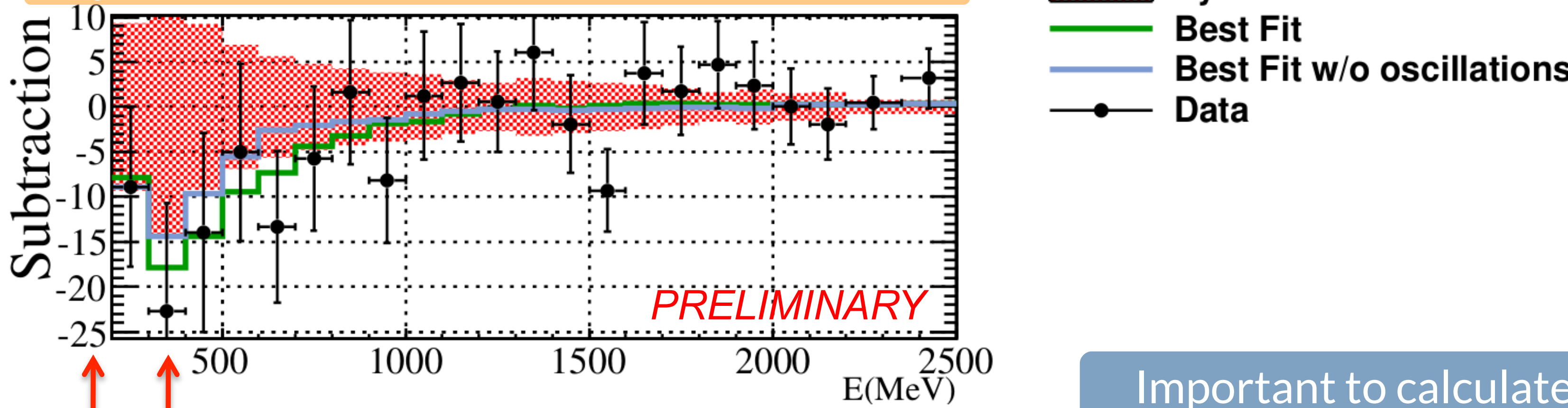
T2K **arXiv:1410.8811**

Binned log-likelihood ratio analysis

$$\chi^2 = \chi^2_{\upsilon_e} + \chi^2_{\gamma} + \textit{penalty term}(\vec{f})$$

Nuisance parameters to model the systematics

ν_eCC: Subtraction to the nominal prediction



L/E ~ 1.5 **L/E ~ 0.7**

Best fit parameters

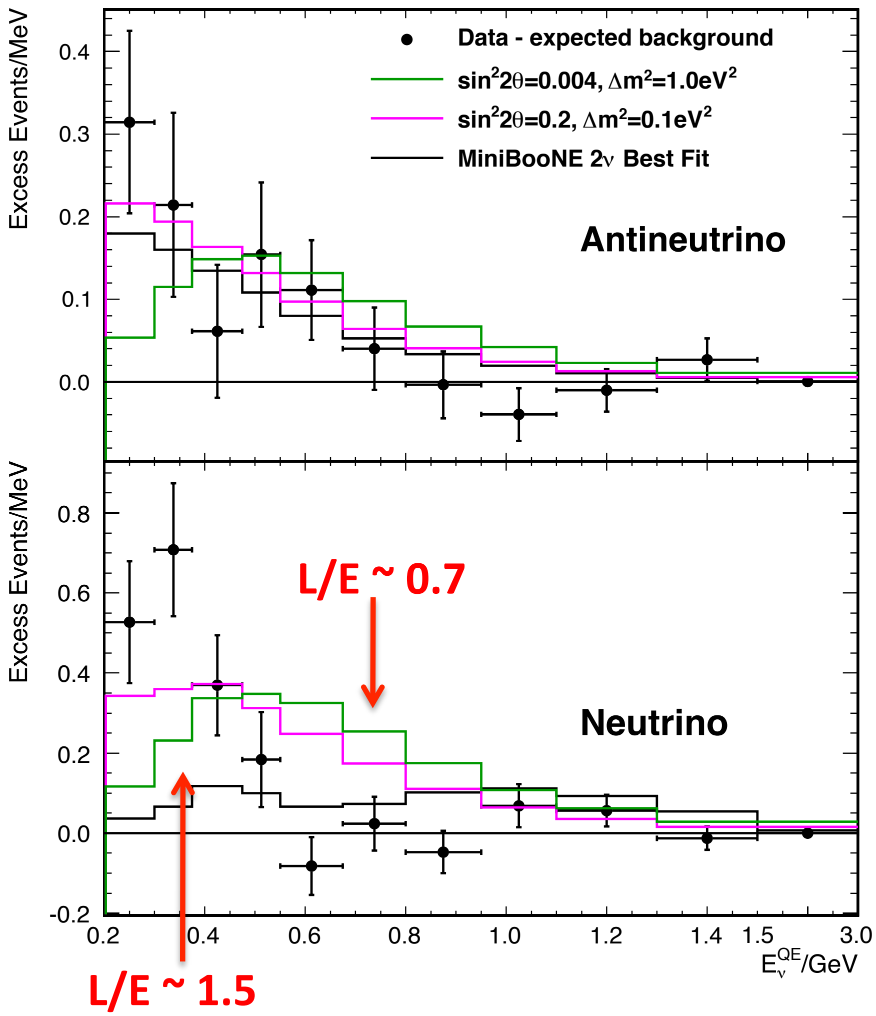
$$\Delta m^2_{41bf} = 2.14\,\mathrm{eV}^2$$

$$\sin^2(2\theta_{ee})_{bf} = 1.00$$

Important to calculate the significance

MiniBooNE Neutrino Oscillation Results

Phys. Rev. Lett. 110, 161801 (2013)



Antineutrino Event Excess from 200-1250 MeV = 78.4+-20.0+-20.3 (2.8σ)

Neutrino Event Excess from 200-1250 MeV = 162.0+-28.1+-38.7 (3.4σ)

Combined Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)

More Exotic SBL Possibilities

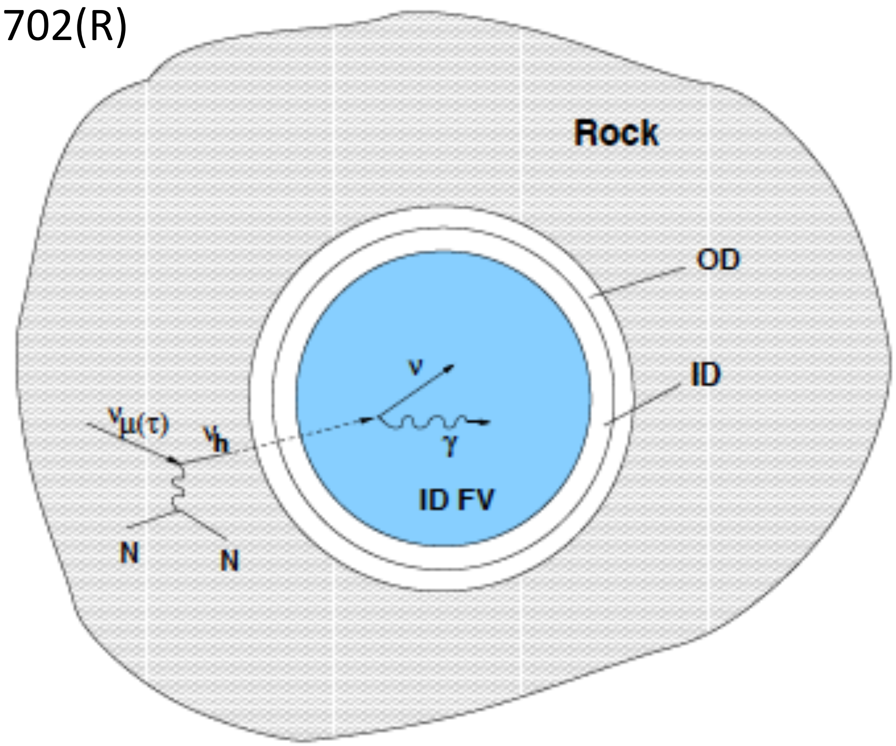
- Sterile Neutrino Decay
- Light WIMP Production (Light WIMPs can behave like neutrinos)
- Sterile Neutrino Self Interactions & New Vector Bosons
- Lorentz Violation & CPT Violation
- Extra Dimensions (active neutrinos are stuck on the brane, while sterile neutrinos can propagate in the bulk)
- Mass-Varying Neutrinos
- etc.

Sterile neutrino decay as a common origin for LSND/MiniBooNe and T2K excess events

S.N. Gninenko
Institute for Nuclear Research, Moscow 117312
(Dated: February 29, 2012)

We point out that the excess of electron-like neutrino events recently observed by the T2K collaboration may have a common origin with the similar excess events previously reported by the LSND and MiniBooNE experiments and interpreted as a signal from the radiative decays of a sterile neutrino ν_h with the mass around 50 MeV produced in ν_μ neutral current (NC) interactions. In this work we assumed that the ν_h can also be produced in ν_τNC reactions.

Phys. Rev. D85 (2012) 051702(R)
arXiv:1107.0279



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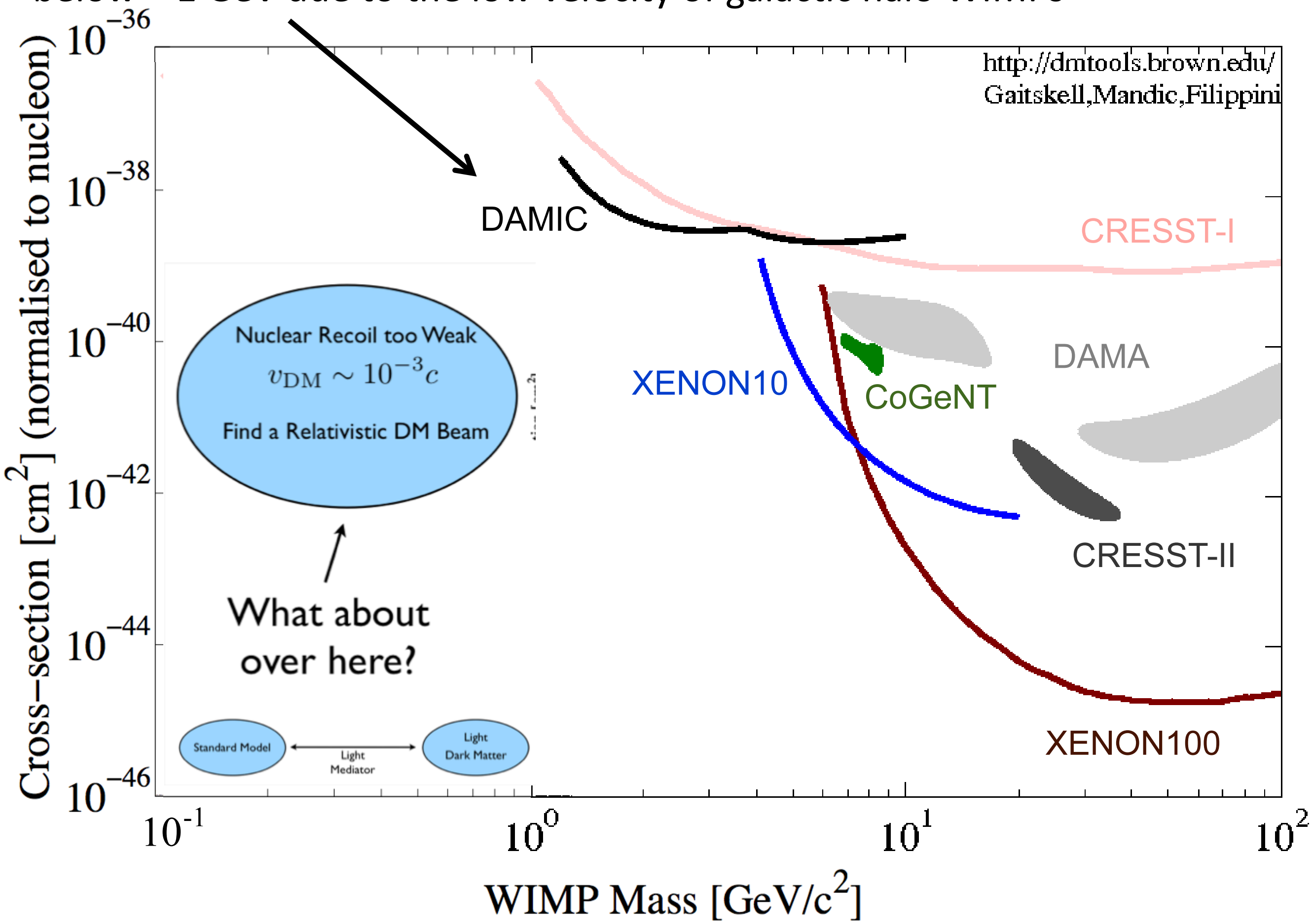
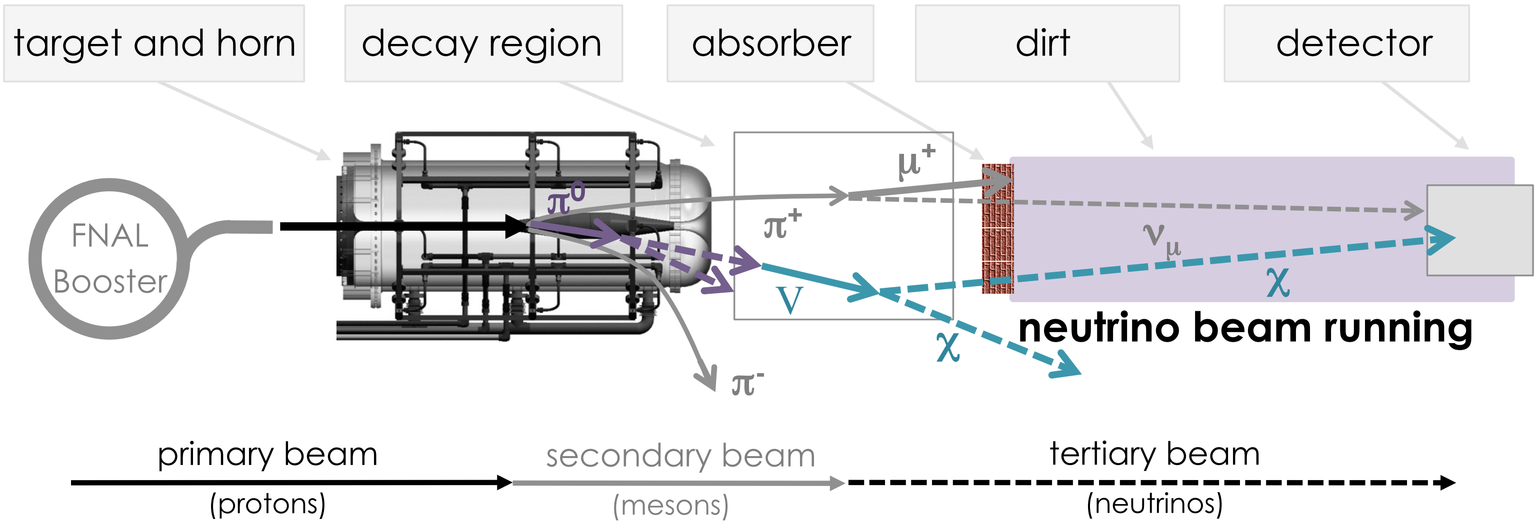
World Data on Low Mass Spin Independent WIMP Scattering

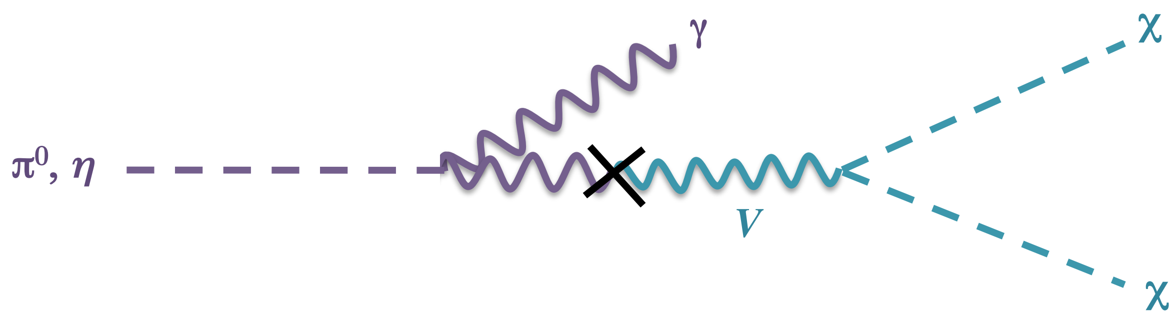
Traditional underground direct detection experiments run out of sensitivity below ~1 GeV due to the low velocity of galactic halo WIMPs



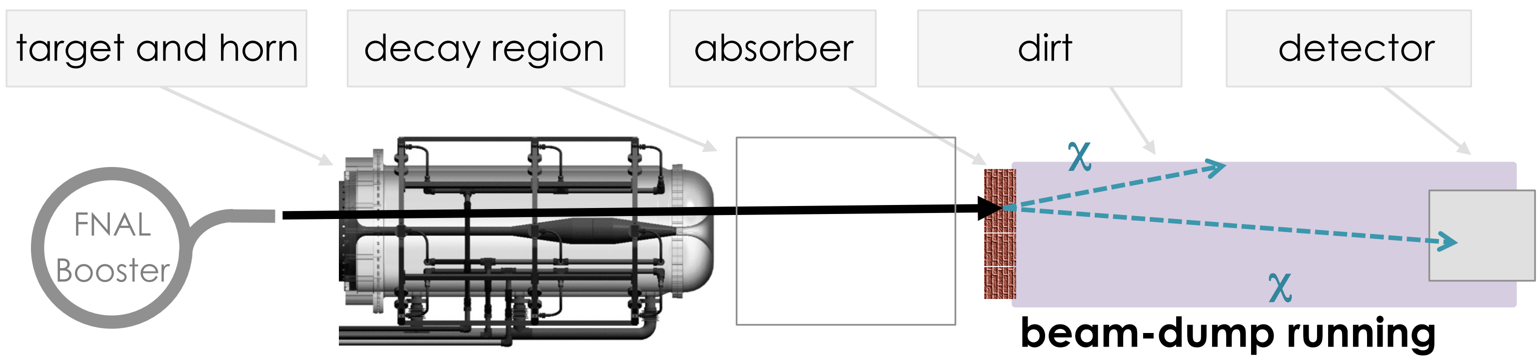
- Lee Weinberg limit (SM mediators W, Z) implies M_{wimp} >> 2GeV
- However, for low mass DM you need a new mediator to produce the right relic density!

Light dark matter production in BNB and detection in MiniBooNE

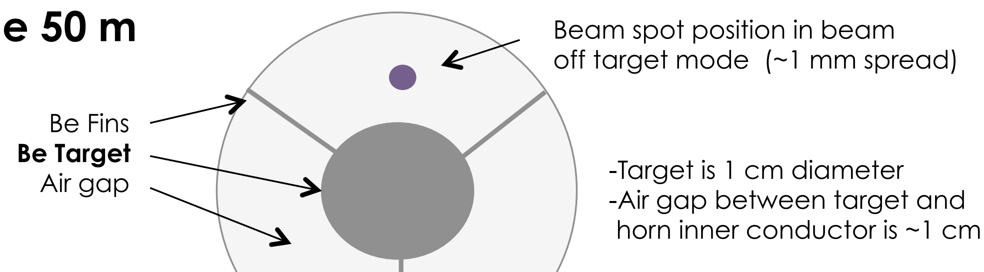




Beam off-target (beam-dump) running



MiniBooNE has the capability to steer the protons past the target and onto the 50 m iron dump (absorber)

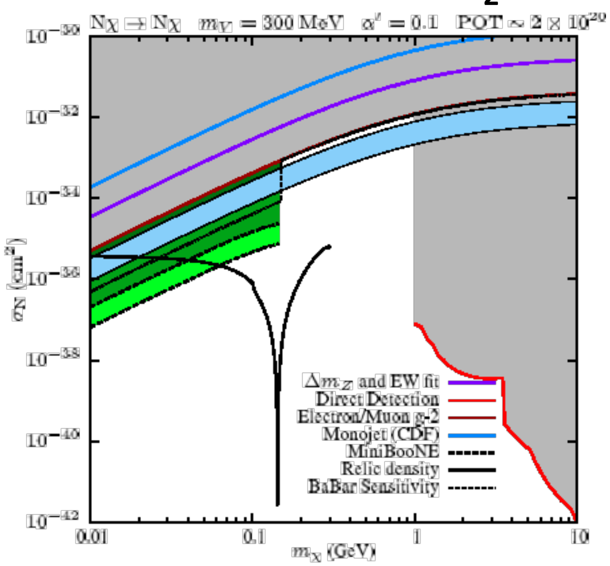


π^0 and η produced by protons in the Fe quickly decay producing dark matter.

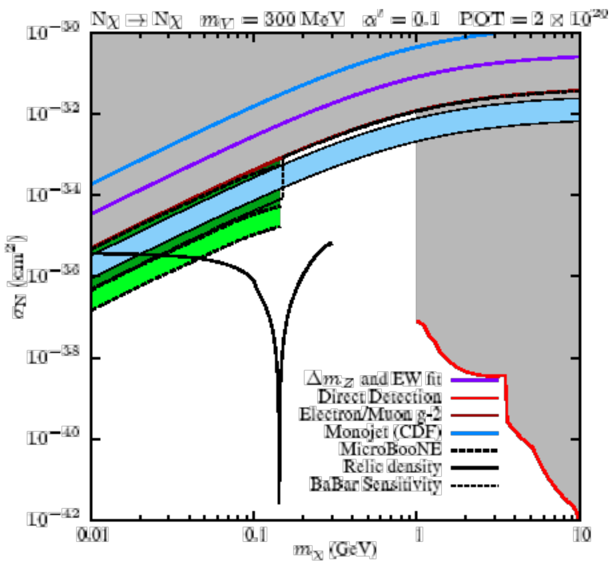
Charged mesons are absorbed in the Fe before decaying, which significantly reduces the neutrino flux (still some production from proton-Air interactions), while leaving the signal unaffected.

Signal Sensitivities for DM-NUCLEON Scattering (2E20 POT)
Cross Section vs. Dark Matter Mass

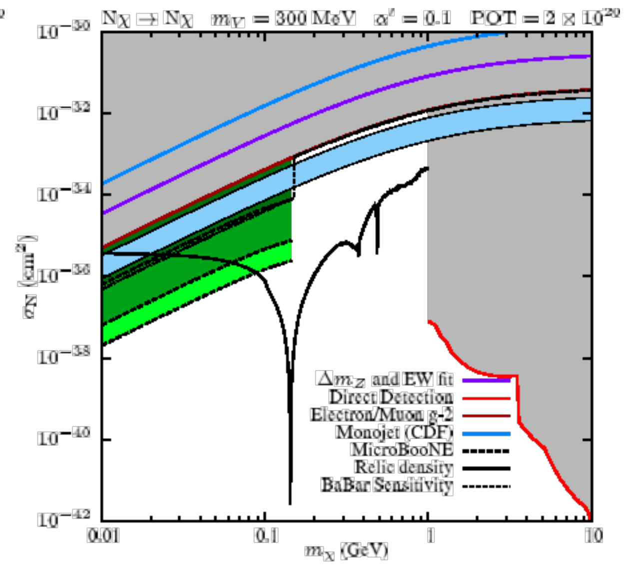
MiniBooNE-CH_2



MicroBooNE-LAr



LAr1-NearDetector



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.
- **The LAr1-ND near detector does an order of magnitude better!**

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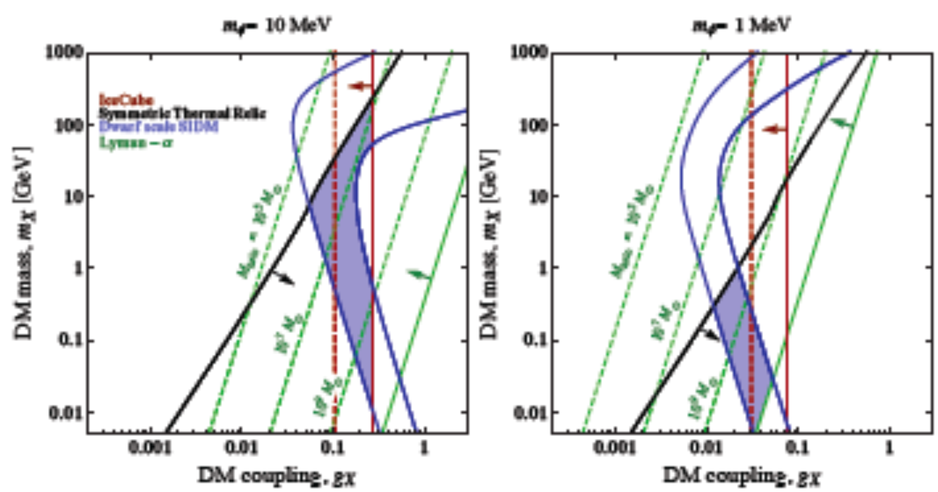
Neutrino Portal Dark Matter: From Dwarf Galaxies to IceCube

John F. Cherry,[1,*] Alexander Friedland,[1,†] and Ian M. Shoemaker[2,‡]

[1] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2] *CP[3]-Origins & Danish Institute for Advanced Study DIAS, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark*

It has been suggested that the baseline scenario of collisionless cold dark matter over-predicts the numbers of satellite galaxies, as well as the dark matter (DM) densities in galactic centers. This apparent lack of structure at small scales can be accounted for if one postulates neutrino-DM and DM-DM interactions mediated by light $\mathcal{O}$(MeV) force carriers. In this letter, we consider a simple, consistent model of neutrinophilic DM with these features where DM and a "secluded" SM-singlet neutrino species are charged under a new $U(1)$ gauge symmetry. An important ingredient of this model is that the secluded sector couples to the Standard Model fields only through neutrino mixing. We observe that the secluded and active neutrinos recouple, leading to a large relic secluded neutrino population. This relic population can prevent small-scale halos from collapsing, while at same time significantly modifying the optical depth of ultra-high-energy neutrinos recently observed at Icecube. We find that the bulk of the parameter space accommodating an (a)symmetric thermal relic has potentially observable consequences for the IceCube high energy signal, with some of the parameter ranges already ruled out by the existing data. Future data may confirm this mechanism if either spectral absorption features or correlations with nearby sources are observed.

Sterile neutrino couples to new vector boson and dark matter and couples to SM fields only through neutrino mixing.



arXiv:1411.1071

Conclusion

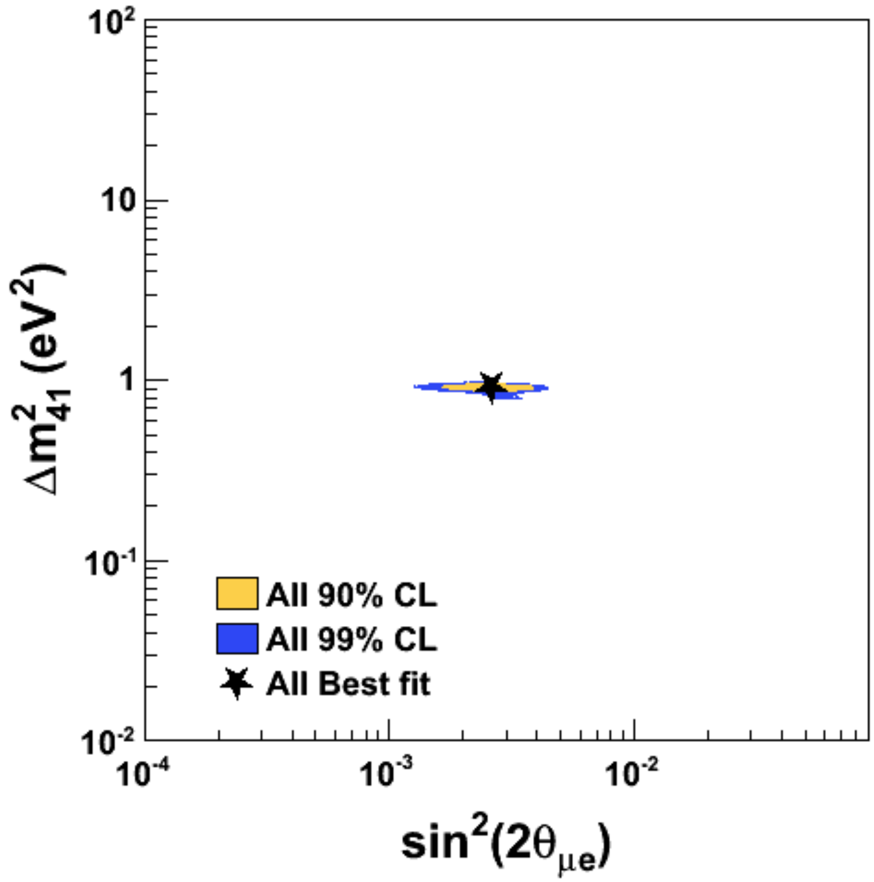
- The anomalies in short baseline ν experiments cannot be explained by the 3 ν paradigm and suggest the existence of sterile neutrinos.
- Future SBL accelerator neutrino experiments have the golden opportunity of proving whether short-baseline oscillations and light, sterile neutrinos exist!
- However, caveats include: (i) Bias in E_ν reconstruction due to nuclear effects; (ii) Competition between ν_e appearance & disappearance; (iii) Complications due to 3+N models with N>1.
- More exotic models are also possible!

Backup

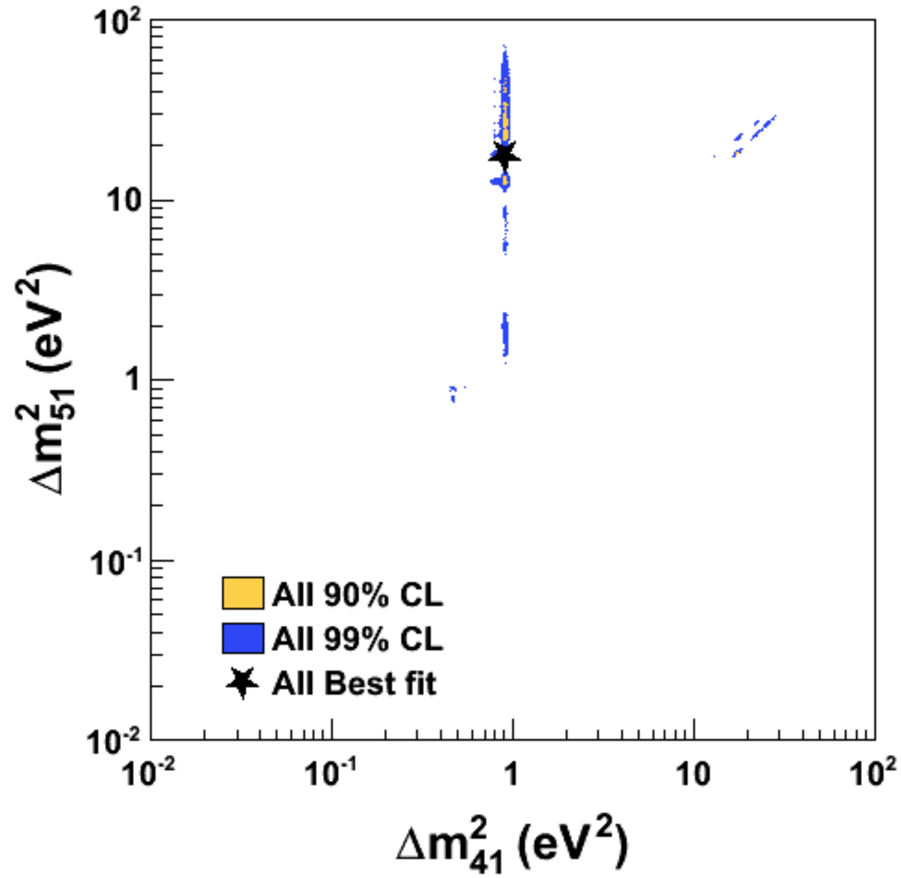
Global 3+N Fits to World Data

J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, & J. Spitz, arXiv:1207.4765

3+1 (P=55%)



3+2 (P=69%)



Note that the Parameter Goodness of Fit probabilities are low due to tension between appearance and disappearance; however, no fake data studies have been performed.

Effect of 3+1 Sterile ν Model on Long-Baseline Expts.

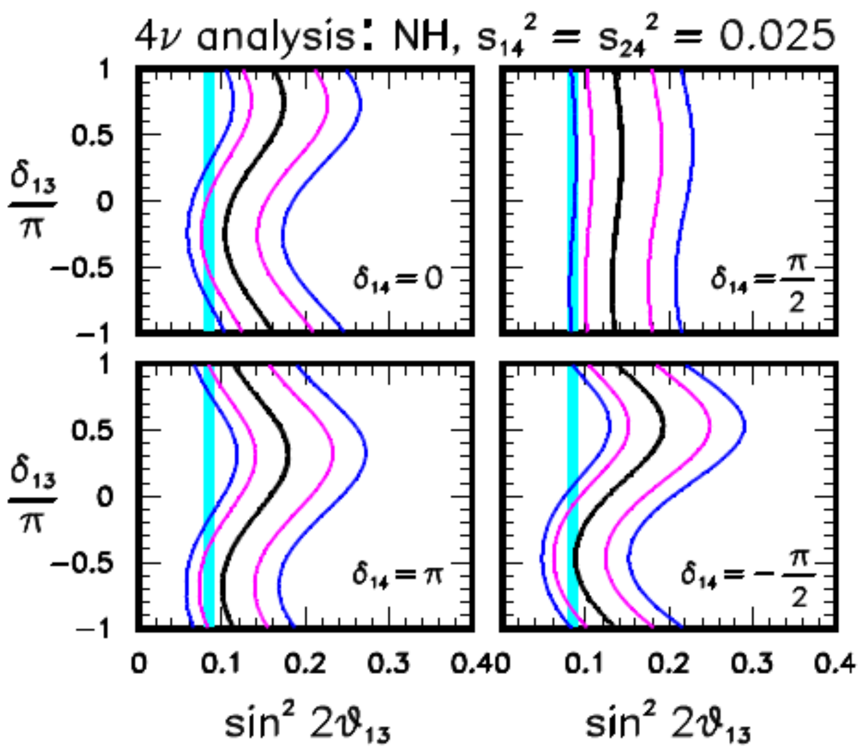


FIG. 3: Regions allowed by T2K for four values of CP-phase δ_{14}. Normal hierarchy is assumed. The mixing angle θ_{23} is marginalized away. The vertical band represents the region allowed by reactor experiments. Confidence levels as in Fig. 2.

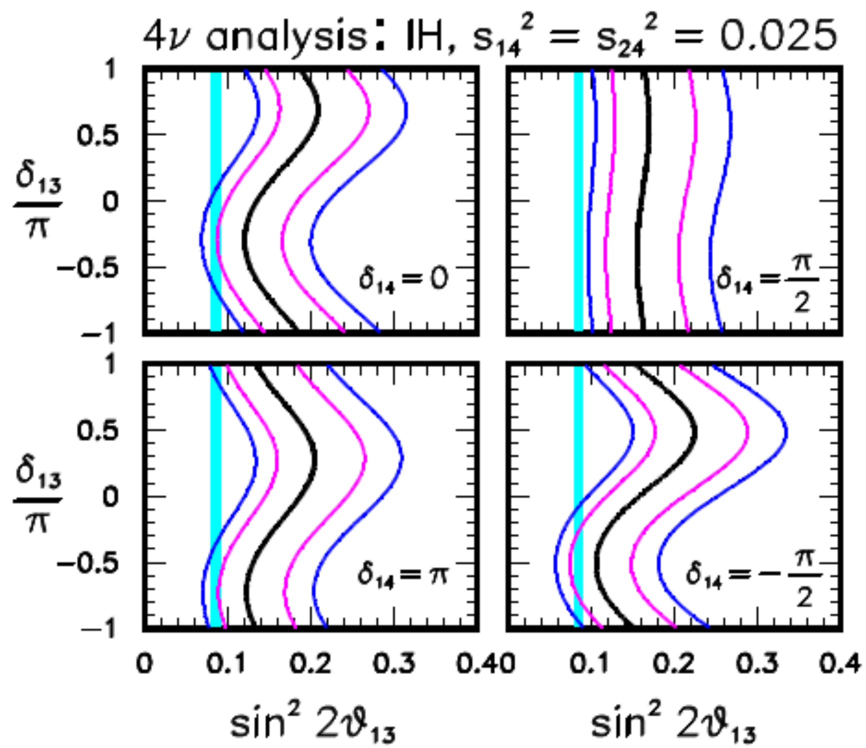


FIG. 4: Regions allowed by T2K for four values of CP-phase δ_{14}. Inverted hierarchy is assumed. The vertical band represents the region allowed by reactor experiments. The mixing angle θ_{23} is marginalized away. Confidence levels as in Fig. 2.

Klop & Palazzo, arXiv:1412.7524

Effect of 3+1 Sterile ν Model on Long-Baseline Expts.

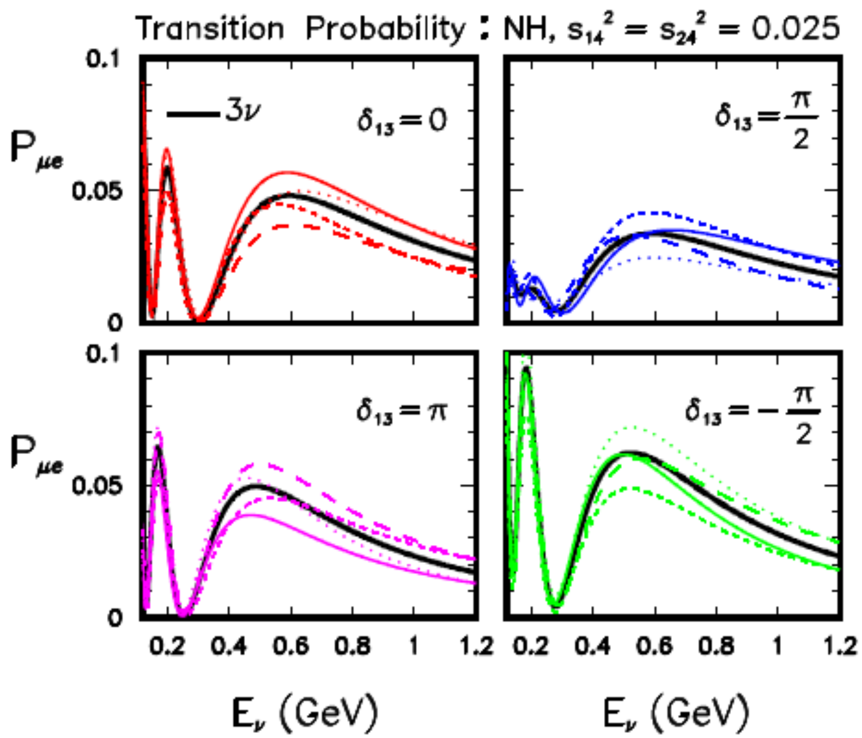
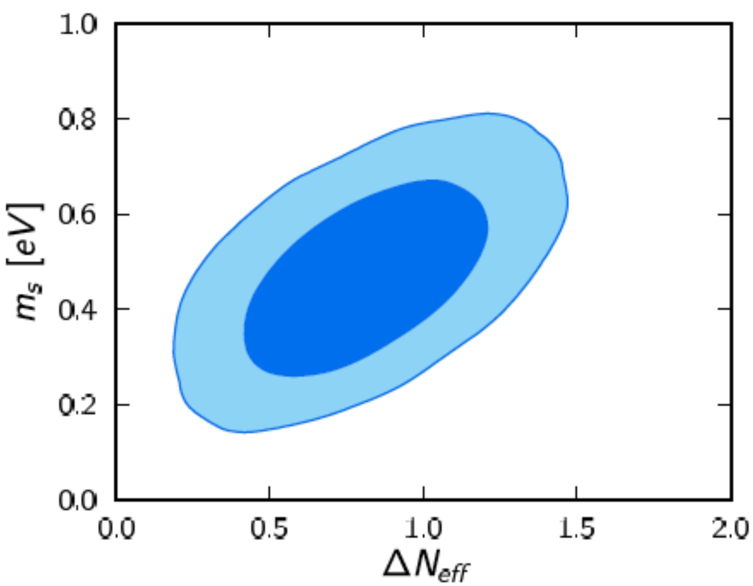


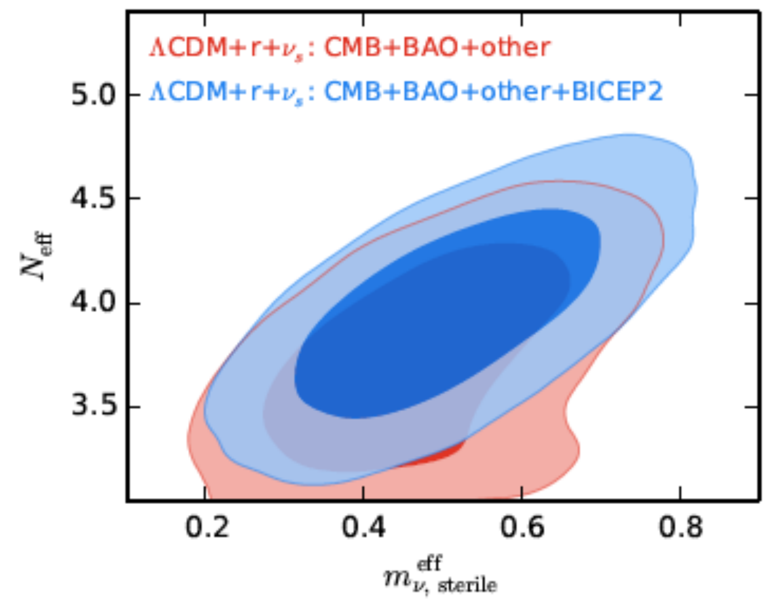
FIG. 7: Probability of $\nu_\mu \to \nu_e$ transition in the 3+1 scheme. The four panels correspond to four different values of the standard CP-phase δ_{13}. In each panel, the black thick solid line represents the 3-flavor case ($\theta_{14} = \theta_{24} = 0$), while the colored lines represent the 4-flavor case (with $s_{14}^2 = s_{24}^2 = 0.025$) for the following four different values of the non-standard CP-phase: $\delta_{14} = 0$ (solid), $\delta_{14} = \pi$ (long-dashed), $\delta_{14} = \pi/2$ (short-dashed), $\delta_{14} = -\pi/2$ (dotted).

Klop & Palazzo, arXiv:1412.7524

Global Cosmology Fits

Including HST H_0 measurement, galaxy cluster data, & BICEP2, the data favor nonzero ΔN_{eff} & m^{eff}_s





Dvorkin, Wyman, Rudd, & Hu, arXiv:1403.8049

Zhang, Li, & Zhang, arXiv:1403.7028

ΔN_{eff} = 0.81+-0.25, m^{eff}_s = 0.47+-0.13 eV

N_{eff} = 3.96+-0.32, m^{eff}_s = 0.51+-0.13 eV

Global Cosmology Fits

Including HST H_0 measurement & galaxy cluster data, the data favor nonzero ΔN_{eff} & m^{eff}_s

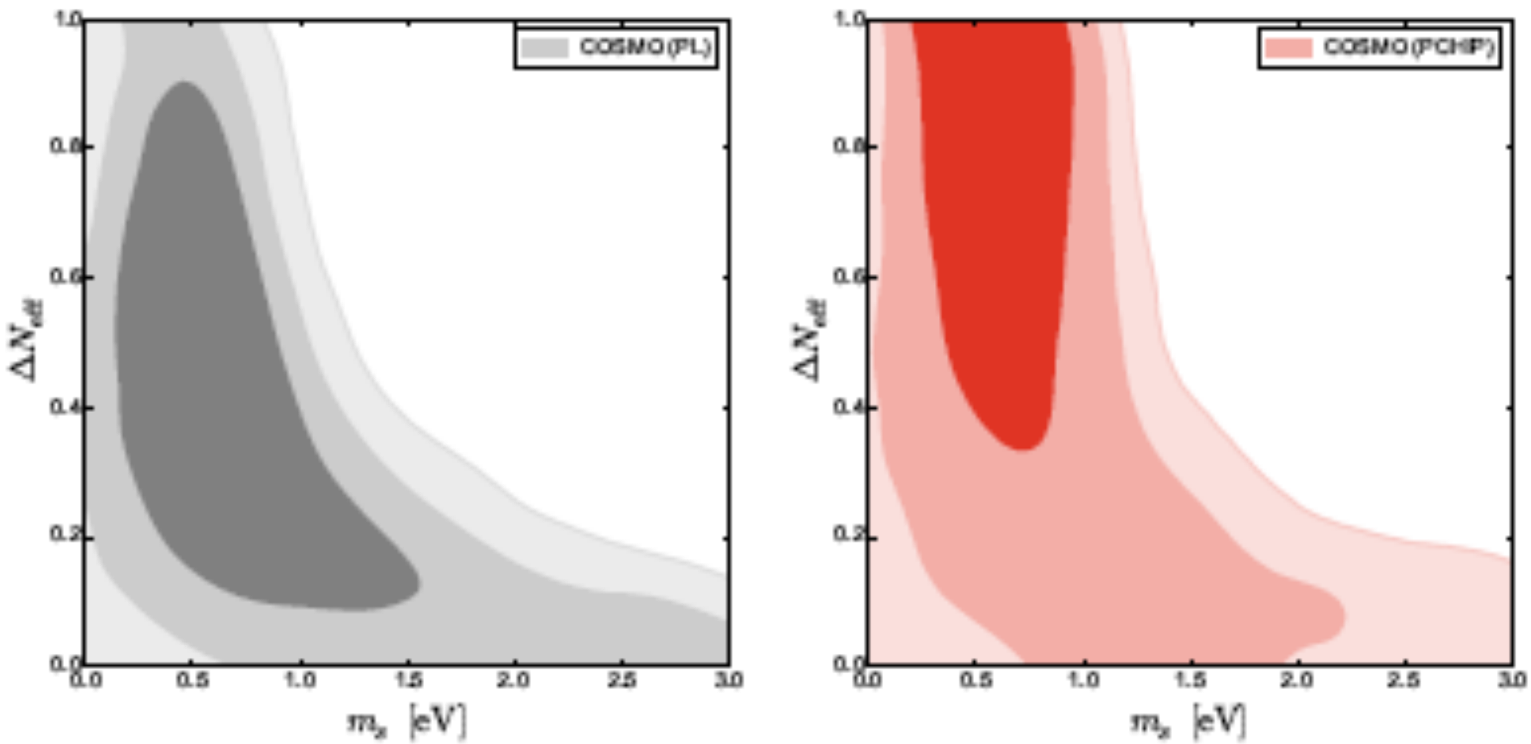
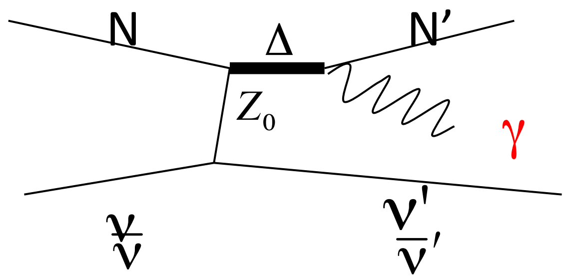


Figure 2. 1σ, 2σ and 3σ marginalized contours in the $m_s - \Delta N_{eff}$ plane in the fits without the SBL prior. The left and right panels correspond, respectively, to the standard power-law PPS and the PCHIP PPS analyses.

Gariazzo, Giunti, & Laveder, arXiv:1412.7405

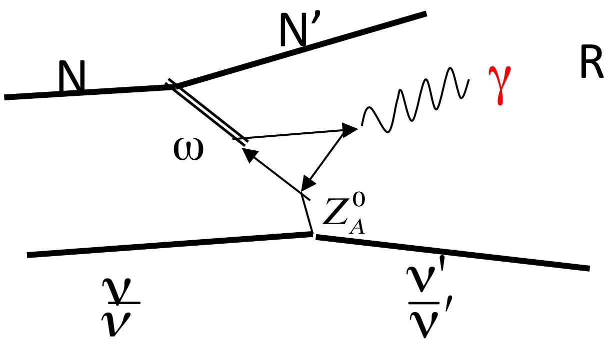
NCγ Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

Dominant processes accounted for in MC!

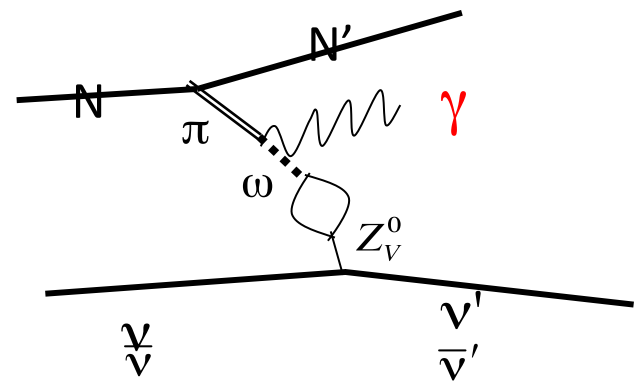


($G^2\alpha/\alpha_S$)

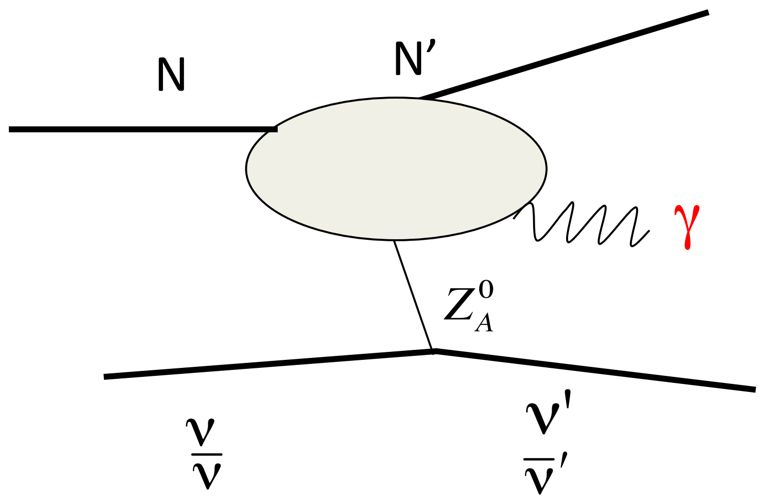
Radiative Delta Decay



Axial Anomaly



Other PCAC



So far no one has found a NC process to account for the ν low-energy excess. Publications:

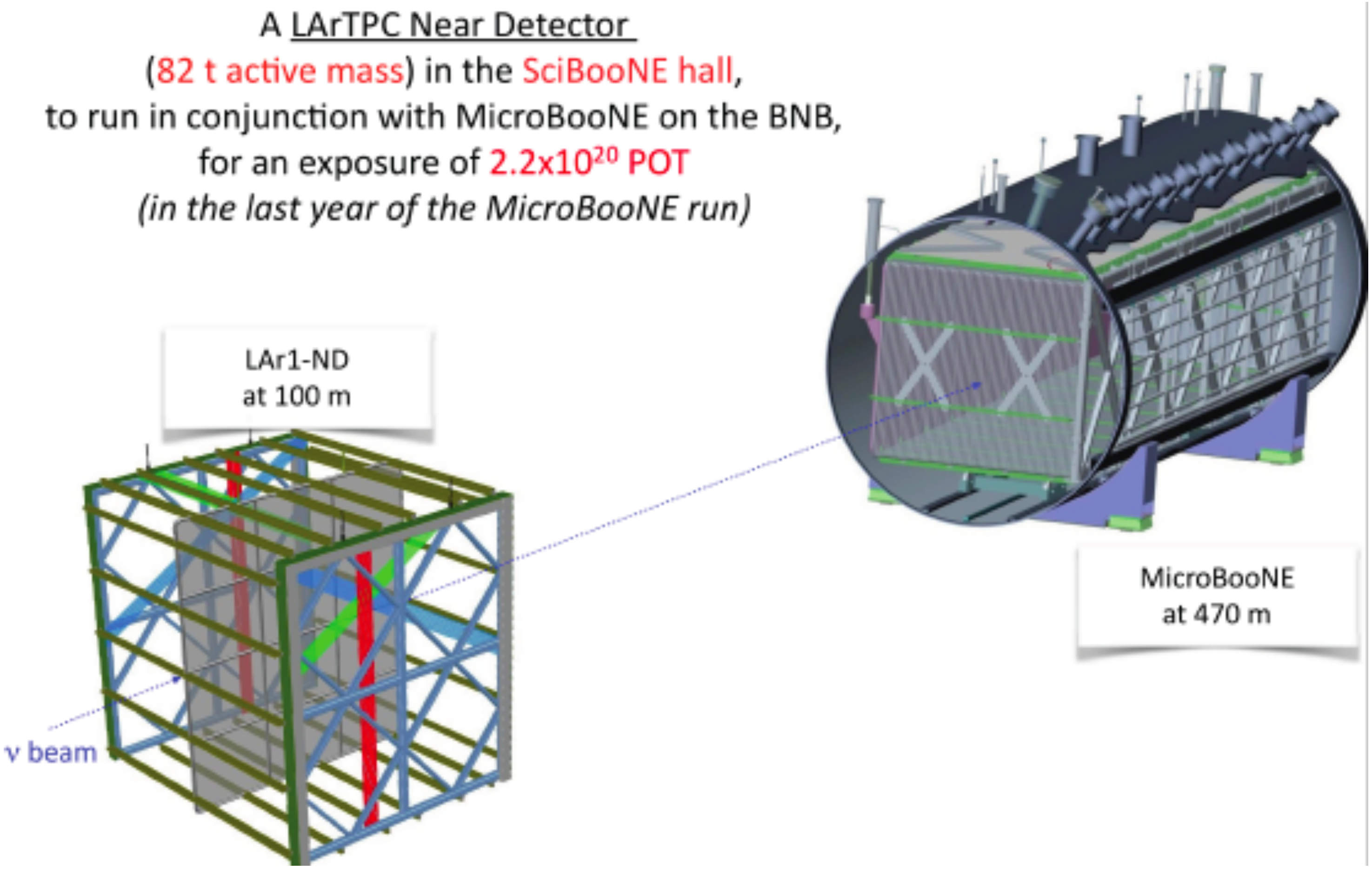
R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

Zhang & Serot, arXiv:1210.3610

Wang, Alvarez-Ruso, & Nieves, arXiv:1407.6060

Summary of the LAr1-ND Proposal

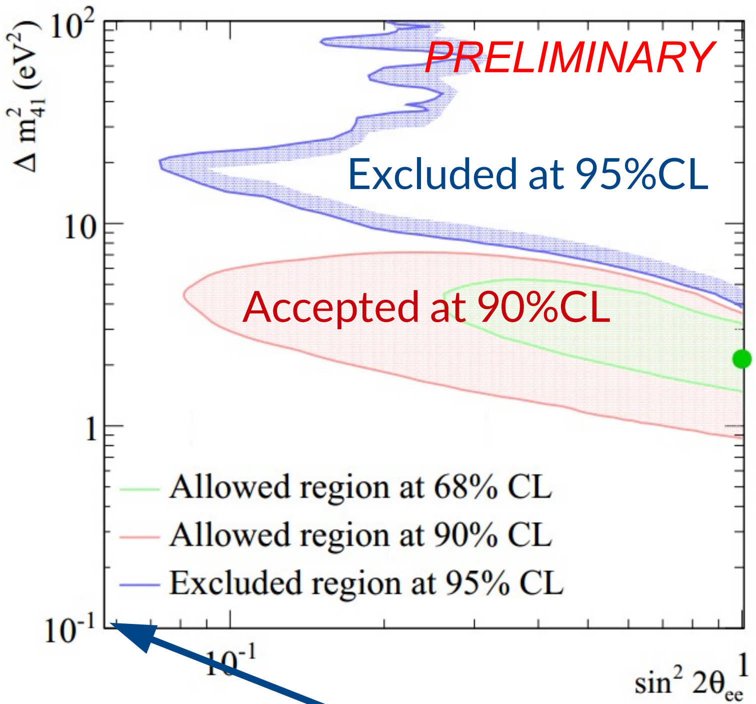


Confidence intervals

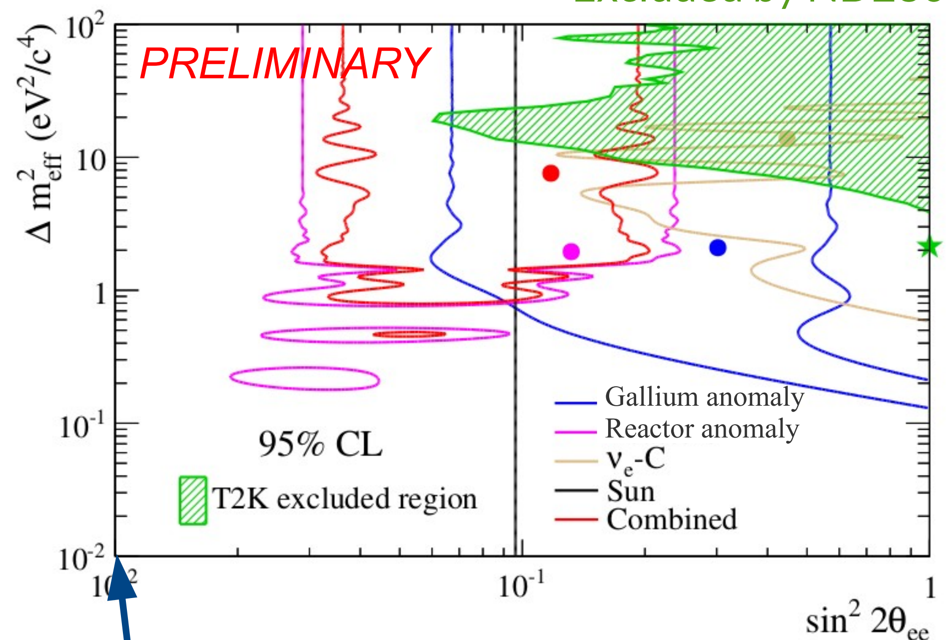
T2K **arXiv:1410.8811**

*Used the **Feldman & Cousins** method to extract the confidence contours*

ND280 results



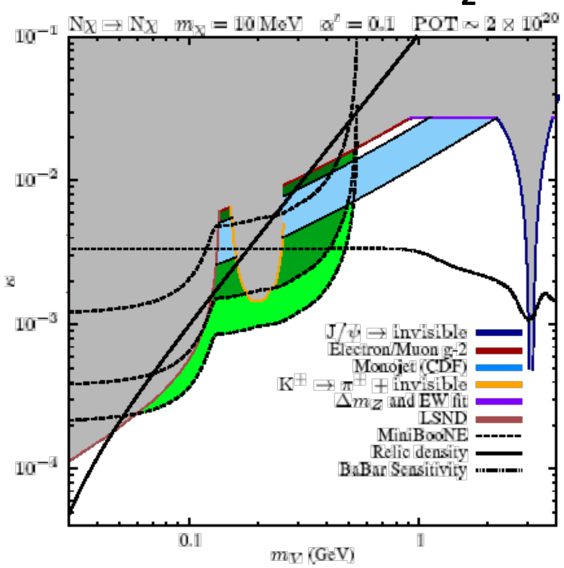
Excluded by ND280



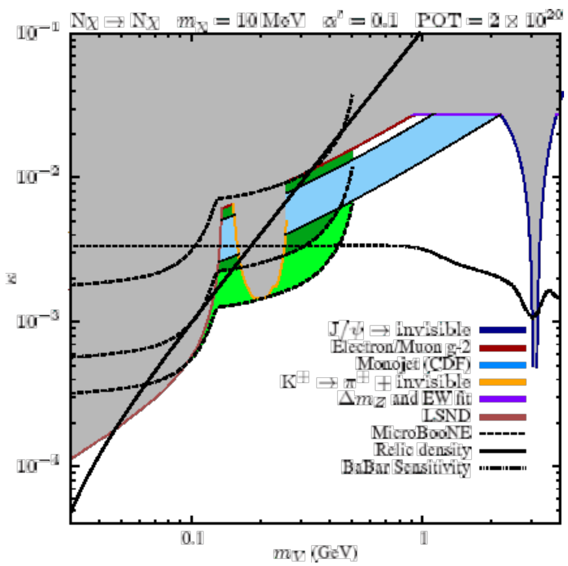
Null hypothesis
excluded at ~94%CL

Signal Sensitivities for DM-NUCLEON Scattering (2E20 POT)
Mixing Strength vs. Vector Mediator Mass

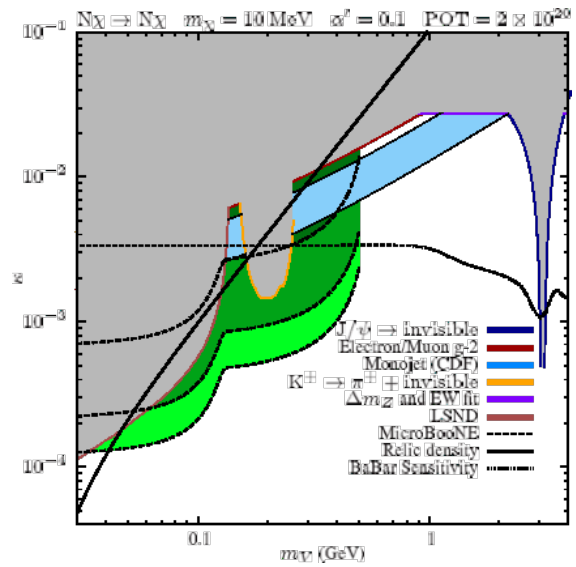
MiniBooNE-CH_2



MicroBooNE-LAr



LAr1-NearDetector



- Signal events: Dark Green > 1000; Green: 10-1000; Light Green: 1-10
- These are signal sensitivity plots. Actual measurement sensitivities/limits will depend on background rates and systematic errors.
- **The LAr1-ND near detector does an order of magnitude better!**